PERFORMANCE ANALYSIS OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR (IPMSM) DRIVE SYSTEM USING DIFFERENT SPEED CONTROLLERS

A Thesis submitted in partial fulfillment of the requirements for the degree of
Master of Technology
In
Electrical Engineering
(Power Control & Drives)

By

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Dedicated to my beloved parents…!!!

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

CERTIFICATE

This is to certify that the thesis entitled **"PERFORMANCE ANALYSIS OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTOR (IPMSM) DRIVE SYSTEM USING DIFFERENT SPEED CONTROLLERS"** being submitted by **HRUSHIKESH MEHER**, **Roll No.: 211EE2133** in partial fulfillment of the requirements for the award of the degree of "**Master of Technology**" in Electrical Engineering specializing in "**Power Control and Drives"** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision. To the best of my knowledge and belief, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:
Place:

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CONTENTS

ABBREVIATIONS

AHCC	-Adaptive Hysteresis Current Control
BLDCM	-Brushless DC Machine
FLC	- Fuzzy Logic Controller
FIS	- Fuzzy Inference System
HB	-Hysteresis Band
HEV	-Hybrid Electric Vehicle
HPI-FLC	-Hybrid PI- Fuzzy Logic Controller
IPMSM	-Interior Permanent Magnet Synchronous Machine
MF	- Membership Function
PI	-Proportion Integral
PM	-Permanent Magnet
PMAC	-Permanent Magnet Alternating Current
PMDC	-Permanent Magnet Direct Current
PMSM	-Permanent Magnet Synchronous Machine
PWM	-Pulse Width Modulation
SMPMSM	-Surface Mounted Permanent Magnet Synchronous Machine
VSI	-Voltage Source Inverter

NOTATIONS

B	-Friction
e	- Speed error
Δe	- Change in error
f_s	-Switching Frequency
i_a, i_b, i_c	-Three Phase Currents
i_d	-d-axis Current
i_f	-Equivalent Permanent Magnet Field Current
i_q	-q-axis Current
J	-Inertia
L_d	-d-axis Self Inductance
L_q	-q-axis Self Inductance
L_s	-Equivalent Self Inductance per Phase
P	-Number of Poles
R_s	-stator resistance
t_1	-Conduction Time or on Time of a Device in a Switching Cycle
t_2	- Device off Time in a Switching Cycle
T_e	-Develop Torque
T_L	- Load Torque
V_a, V_b, V_c	-Three Phase Voltage
V_d	-d-axis Voltage
V_q	-q-axis Voltage
V_s	-Stator Voltage Phasor
v_f	-Back EMF
λ_d	-Flux Linkage due d axis
λ_f	-PM Flux Linkage or Field Flux Linkage
λ_q	-Flux Linkage due q axis
θ_r	-Rotor Position
μ	-Permeability
ω_m	- Rotor Speed
ω_r	-Electrical Speed

ABSTRACT

The present research is indicating that the Permanent magnet motor drive could become serious competitor to the induction motor drive for servo application. Further, with the evolution of permanent magnet materials and control technology, the Permanent Magnet Synchronous Motor (PMSM) has become a pronounced choice for low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles due to its special features like high power density, high torque/inertia ratio, high operating efficiency, variable speed operation, reliability, and low cost etc. Here we deals with the detailed modeling of an IPMSM drive system with Hybrid PI-Fuzzy logic controller (PI-FLC) as speed controller and Adaptive Hysteresis Current Controller as torque controller by controlling the current components of torque.

In this thesis we deals with a simulation for speed control and improvement in the performance of a closed loop vector controlled IPMSM drive which employ two loops for better speed tracking and fast dynamic response during transient as well as steady state conditions by controlling the torque component of current. The outer loop employ Hybrid PI-Fuzzy logic controller (PI-FLC) while inner loop as Adaptive Hysteresis Band Current Controller (AHBCC) designed to reduce the torque ripple. Despite proportional plus Integral (PI) controller are usually preferred as speed controller due to its fixed gain (K_p) and Integral time constant (K_i), the performance of PI controller are affected by parameters variations, speed change and load disturbances in PMSM, due to which it results to unsatisfied operation under transient conditions. The drawbacks of PI controller are minimized using fuzzy logic controller (FLC). So for this a fuzzy control technique is also designed using mamdani type, triangular based 5x5 MFs and selecting the superior functionalities of PI and FLC, a Hybrid PI-FLC designed for effective speed control under transient and steady state condition.

The complete viability of above mentioned integrated control strategy is implemented and tested in the MATLAB/Simulink environment and a performance comparison of proposed drive system with conventional PI, fuzzy logic controller and Hybrid PI-Fuzzy Logic Controller integrated separately as speed controller in terms of steady state and transient analysis with fixed step, variable step load and variable speed condition has been presented. Beside this a detailed comparative study of AHBCC is also done with Conventional Hysteresis Current Control(CHCC) scheme. The simulation circuits parameters for IPMSM, inverter, speed and current controllers of the drive system are given in Appendix-A.

LIST OF FIGURES

CHAPTER 1

Introduction

From the last three decades AC machine drives are becoming more and more popular, especially Induction Motor Drives (IMD) and Permanent Magnet Synchronous Motor (PMSM), but with some special features, the PMSM drives are ready to meet sophisticated requirements such as fast dynamic response, high power factor, and wide operating speed range like high performance applications, as a result, a gradual gain in the use of PMSM drives will surely be witness in the future market in low and mid power applications.

Now in a permanent magnet synchronous machine, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic field. Having the magnets on the rotor, some electrical losses due to field winding of the machine get reduced and the absence of the field losses improves the thermal characteristics of the PM machines hence its efficiency. Also lack of mechanical components such as brushes and slip rings makes the motor lighter, high power to weight ratio which assure a higher efficiency and reliability. With the advantages described above, permanent magnet synchronous generator is an attractive solution for wind turbine applications also. Like always, PM machines also have some disadvantages: at high temperature, the magnet gets demagnetized, difficulties to manufacture and high cost of PM material.

PM electric machines are classified into two groups: PMDC machines and PMAC machines. The PMDC machines are similar with the DC commutator machines; the only difference is that the field winding is replaced by the permanent magnets while in case of PMAC the field is generated by the permanent magnets placed on the rotor and the sliprings, the brushes and the commutator does not exist in this machine type. For this reason the machine is simpler and more attractive to use instead of PMDC. PMAC can be classified depending on the type of the back electromotive force (EMF): Trapezoidal type and

Sinusoidal type. Sinusoidal type PM machine can further be classified as Surface mounted PMSM and Interior PMSM. The classification can be shown as below:

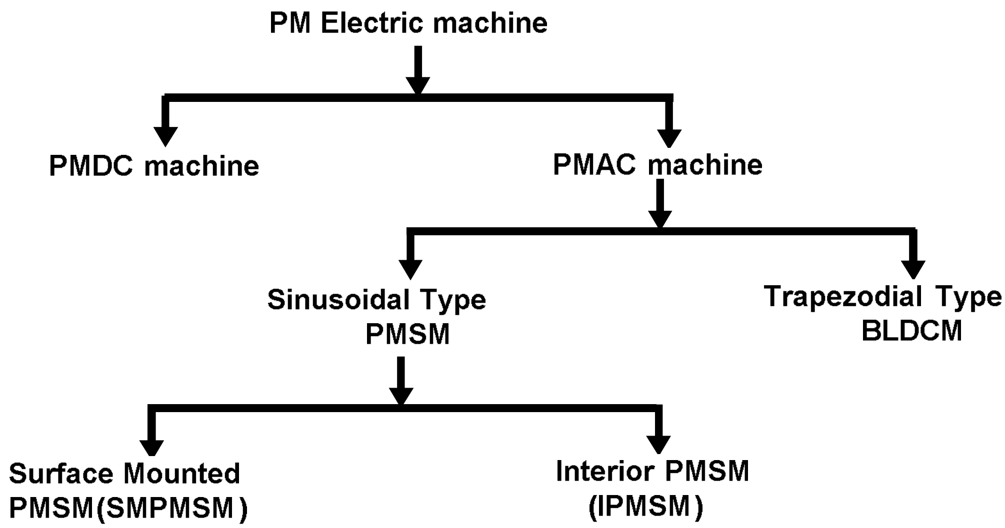


Figure.1.1 Classification of Permanent Magnets Machines

The trapezoidal PMAC machines also called Brushless DC motors (BLDC) has a trapezoidal-shaped back EMF and develop trapezoidal back EMF waveforms with following characteristics:

- Rectangular current waveform
- Rectangular distribution of magnet flux in the air gap
- Concentrated stator windings.

While the sinusoidal PMAC machines, called Permanent magnet synchronous machines (PMSM) has a sinusoidal-shaped back EMF and develop sinusoidal back EMF waveforms with following characteristics:

- Sinusoidal current waveforms
- Sinusoidal distribution of magnet flux in the air gap
- Sinusoidal distribution of stator conductors.

Based on the rotor configuration the PM synchronous machine can be classified as:

(a) Surface mounted magnet type (SPMSM):

In this case the magnets are mounted on the surface of the rotor as shown in fig.1.2. The magnets can be regarded as air because the permeability of the magnets is close to unity ($\mu = 1$) and the saliency is not present due to same width of the magnets. Therefore the inductances expressed in the quadrature coordinates are equal ($L_q = L_d$). In the case of SPMSM the saliency is not present, making this machine easier to design, becoming an attractive solution for wind turbine application.

(b) Interior magnet type (IPMSM):

In this type the motor, the magnets are place inside the rotor which is shown in fig.1.3.In this configuration saliency is available and the air gap of d-axis is greater compared with the q axis gap resulting that the q axis inductance has a different value than the d axis inductance. There is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation. These motors are considered to have saliency with q axis inductance greater than the d axis inductance (L_q>L_d). Due to saliency IPMSM is a good candidate for high-speed operation such as PCB manufacturing, spindle drives and hybrid electric vehicles (HEV) etc.

Furhter, among Interior Permanent Magnet Synchronous Motor (IPMSM) and Surface Mounted Permanent Magnet Synchronous Motor (SMPMSM), IPMSM is preferably used for many application due to its constructional features alongwith higher demagnetizing effect to enhance the speed above the base speed. Although IPMSM demand gradually increasing in various industrial applications with varacious speed control and fast dynamic response, there still exist a great challenge to control its speed more accurately under various conditions.

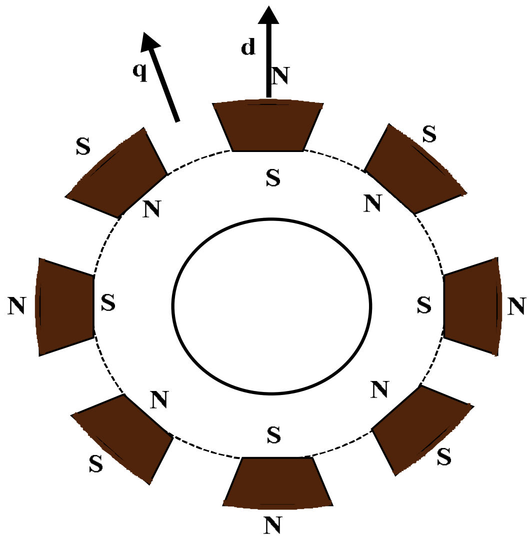


Fig.1.2 Surface PM (SPM) Synchronous Machine

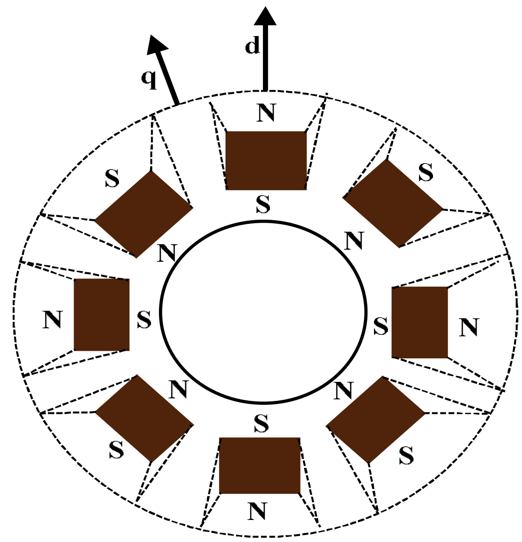


Fig.1.3 Interior PM (IP) Synchronous Machine

Vector control (or Field Oriented Control) principle makes the analysis and control of Permanent Magnet Synchronous Motor (PMSM) drives system simpler and provides better dynamic response. It is also widely applied in many areas where servo- like high performance plays a secondary role to reliability and energy savings. To achieve the field-oriented control of PMSM, knowledge of the rotor position is required. Usually the rotor position is measured by a shaft encoder, resolver, or hall sensors.

In the PMSM, excitation flux is set-up by magnets; subsequently no magnetizing current is needed from the supply. This easily enables the application of the flux orientation mechanism by forcing the d-axis component of the stator current vector (i_d) to be zero. As a result, the electromagnetic torque will be directly proportional to the q-axis component of the stator current vector (i_q), hence better dynamic performance is obtained by controlling the electro-magnetic torque separately. This thesis presents the field oriented vector control scheme for permanent magnet synchronous motor (PMSM) drives, that regulates the speed of the PMSM, is provided by a quadrature axis current command developed by the speed controller. PI controller cab be preferably used for outer speed control loop but because of its fixed proportional gain constant and integral time constant, the behaviour of the PI controllers are affected by parameter variations, load disturbances and speed fluctuation [23] [24]. To overcome the problem of PI controller, here a Fuzzy controller has been designed and implemented and finally taking the superior performances of PI and Fuzzy controller, a Hybrid PI-Fuzzy controller has been designed and implemented as outer speed loop which provides the reference quadrature axis current to the current controller. The conventional hysteresis band current controller has proven that, it is most suitable for current regulated VSI fed ac drives due to its simplicity and fast speed tracking. However it has certain limitations like large current ripple in steady state and a variable switching frequency operation during motor load changes. So here an adaptive hysteresis current controller in which the hysteresis band is programmed as a function of variation of motor speed and load current has been implemented. The proposed current control strategy is applied to the inner loop of the vector controlled permanent magnet synchronous motor (PMSM) drive system in order to reduce the torque ripple during load variation.

Finally a performance comparison study of proposed model using PI, FLC and Hybrid PI-FLC separately as outer speed loop with adaptive hysteresis band current controller as inner current loop has been presented in terms of steady state and transient analysis with fixed step, variable step load and variable speed condition using MATLAB/Simulink environment.. Beside this a detailed comparative study of AHBCC is also done with Conventional Hysteresis Current Control (CHCC) scheme on the basis of simulation results.

1.1. Research background:

PM motor drives have been a topic of interest for the last twenty years. Different authors have carried out modelling and simulation of such drives. This section offers a brief review of some of the published work on the PMSM drive system:

In 1986 Jahns, T.M., Kliman, G.B. and Neumann, T.W. [1] discussed that interior permanent magnet (IPM) synchronous motors possessed special features for adjustable speed operation which distinguished them from other classes of ac machines. The rotor magnetic saliency preferentially increased the quadrature-axis inductance and introduced a reluctance torque term into the IPM motor's torque equation. The control of the sinusoidal phase currents in magnitude and phase angle with respect to the rotor orientation provided a means for achieving smooth responsive torque control. A basic feed forward algorithm for executing this type of current vector torque control was also discussed, including the implications of current regulator saturation at high speeds.

High energy magnets in IPM motor is used on its rotor to improve the performance of the rotor. Over this topology Sebastian, T. Slemon, G. R. and Rahman, M. A. [2] in 1986, reviewed permanent magnet synchronous motor advancements and presented equivalent electric circuit models for such motors and compared computed parameters with measured parameters.

Pillay and Krishnan, R. [3] in 1988, presented PM motor drives and classified them into two types such as permanent magnet synchronous motor drives (PMSM) and brushless dc motor (BDCM) drives. The PMSM has a sinusoidal back emf and requires sinusoidal stator currents to produce constant torque while the BDCM has a trapezoidal back emf and requires rectangular stator currents to produce constant torque. The PMSM is very similar to the wound rotor synchronous machine except that the PMSM that is used for servo applications tends not to have any damper windings and excitation is provided by a permanent magnet instead of a field winding. Hence the d, q model of the PMSM can be derived from the well-known model of the synchronous machine with the equations of the damper windings and field current dynamics removed. Equations of the PMSM are derived in rotor reference frame and the equivalent circuit is presented without dampers.

Further as an extension of his previous work same author in 1989 [4] presented the application of vector control as well as complete modelling, simulation, and analysis of the drive system in rotor reference frame without damper windings. Performance differences due to the use of pulse width modulation (PWM) and hysteresis current controllers were examined. Particular attention was paid to the motor torque pulsations and speed response.

The current-regulated voltage source inverter (VSI) has the advantage of permitting direct torque control by controlling the amplitude of the currents in the machine armature and their phase with respect to the back-emf. A smooth torque generation at low speeds and the system operating limits in the high and extended speed ranges were investigated by Dhaouadi R. and Mohan N. [5] by using ramp, hysteresis and space vector type current controller and performances of these different controllers were also investigated.

Conventional Hysteresis current control technique is popularly used because of its simplicity of implementation, fast current control response, and inherent peak current limiting capability. However, a current controller with a fixed hysteresis hand has the disadvantage that the modulation frequency varies in a band and, as a result, generates non-optimum current ripple in the load. To overcome above mentioned demerits, Bimal. K. Bose [6] proposed an adaptive hysteresis-band current control method where the band is modulated with the system parameters to maintain the modulation frequency to be nearly constant. Systematic analytical expressions of the hysteresis band were derived as functions of system parameters.

Using the above technique Kale and Ozdemir [7] also proposed an adaptive hysteresis band current controller for active power filter to eliminate harmonics and to compensate the reactive power of three-phase rectifier. The adaptive hysteresis band current controller changes the hysteresis bandwidth according to modulation frequency, supply voltage, dc capacitor voltage and slope of the reference compensator current wave.

In 2004, Jian-Xin, X., Panda, S. K., Ya-Jun, P., Tong Heng, L. and Lam, B. H. [8] applied a modular control approach to a permanent-magnet synchronous motor (PMSM) speed control. Based on the functioning of the individual module, the modular approach enabled the powerfully intelligent and robust control modules to easily replace any existing module which did not perform well, meanwhile retaining other existing modules which were still effective.

Hoang Le-Huy [10] presented a unified method for modelling and simulation of electrical drives using state-space formulation in MATLAB/Simulink. The proposed method has been successfully implemented in a simulation package called “Power System Block set” (PSB) for use in MATLAB/Simulink environment.

An adaptive hysteresis band current control strategy was proposed in [11] by Tae-Won Chun and Meong-Kyu Choi where the hysteresis band is controlled as variations of motor speed, load current, and neutral point voltage in order to hold the switching frequency constant at any operating conditions. The proposed current control strategy was introduced to the current controller of a vector controlled permanent magnet synchronous motor systems.

A review of recently used current control techniques for three-phase voltage source pulse width modulated converters were presented by Kazmierkowski et al. [12] in 1998. Various techniques, different in concept, had been described in two main groups: linear and nonlinear. The first includes proportional integral stationary and synchronous and state feedback controllers and predictive techniques with constant switching frequency. The second comprises bang-bang (hysteresis, delta modulation) controllers and predictive controllers with on-line optimization. New trends in the current control: neural networks and fuzzy-logic based controllers were discussed.

Taking the advantage of the position features of both conventional hysteresis current controller and ramp comparator controller Kadjoudj et al. [13] presented the design and software implementation of a hybrid current controller in 2004. The proposed intelligent controller was a simultaneous combination and contribution of the hysteresis current controller and the ramp comparator.

An improved current controller based on conventional current-regulated delta modulator (CRDM) was proposed by Wipasuramonton et al. which introduce a zero-vector zone and a current error correction technique. It reduces the current ripple and switching frequency at low speeds, without the need to detect the back-emf, as well as the low-frequency error at high speeds. The performance of the modulator was verified by both simulation and measurements on a permanent magnet brushless ac drive [14].

B. K. Bose [15] presented different types of synchronous motors and compared them to induction motors. The modelling of PM motor was derived from the model of salient pole synchronous motor. All the equations were derived in synchronously rotating reference frame and was presented in the matrix form. The equivalent circuit was presented with damper windings and the permanent magnet was represented as a constant current source. Some discussions on vector control using voltage fed inverter were given.

A fuzzy logic based on-line efficiency optimization control of a drive that uses an indirect vector controlled induction motor speed control system in the inner loop was proposed by G. C. D. Sousa, B. K. Bose, and J. G. Cleland in 1995 [17]. The method uses a fuzzy controller to adjust adaptively the magnetizing current based on the drive measured input power, thus yielding true optimum efficiency operation with fast convergence. The pulsating torque problem has been successfully addressed by implementing a feed forward torque compensator.

The fuzzy logic based speed control of an interior permanent synchronous motor (IPMSM) drive was presented by M. N. Uddin and M. A. Rahman [20] in 1999. The fundamentals of fuzzy logic algorithms related to motor control applications were illustrated.

A new fuzzy speed controller for the IPMSM drive has been designed. The efficacy of the proposed fuzzy logic controller (FLC) based IPMSM drive was verified by simulation. It was shown that the drive can follow the command speed without any overshoot and steady state error. It also found that if the number of rules increase, better performances can be attained, but the computational burden will also be increased.

Further the same author M. N. Uddin and M. A. Rahman [19] in 2007 also presented an improved fuzzy logic controller (FLC) for an interior permanent magnet synchronous motor (IPMSM) for high-performance industrial drive applications. Here the FLC was utilized to provide robust performance for speed control. A new and computationally simple FLC was utilized as a speed controller, which mainly controls the q-axis stator current. The parameters of the FLC were tuned by a genetic algorithm (GA), which avoids the long search time for classical fuzzy logics for specific applications. The FLC developed to have less computational burden, which makes it suitable for real-time implementation, particularly at high-speed operating conditions.

M. Nasir Uddin. Ronald S. Rebeiroin 2011 [27] presented a closed loop vector control of an interior permanent magnet synchronous motor (IPMSM) drive incorporating two separate fuzzy logic controllers (FLCs). The first one was designed as an effective speed controller while the second one designed to minimize the developed torque ripple by varying online the hysteresis band limits of the PWM current controller. A performance comparison of the proposed IPMSM drive with conventional PI controller based drive was provided in simulation.

A comparative study on fuzzy rule-base of fuzzy logic speed control with vector-controlled PMSM drive was highlighted by Siti Noormiza Mat Isa, Zulkifilie Ibrahim, Fazlli Patkar [21]. Fuzzy rule-base design was viewed as control strategy. All fuzzy rules contribute to some degree in obtaining the desired performance. However, some rules fired weakly do not contribute significantly to the final result and can be eliminated.

The complexity of PI controller tuning and high response time is overcome by Fuzzy controller which has less response time and high accuracy without any mathematical calculation. A simulation of speed control system on fuzzy logic approach for an indirect vector controlled permanent magnet synchronous drive by applying space vector modulation was presented in [28]. Comparative results for traditional PI controller and Fuzzy logic controller for speed response during start-up under no load, load disturbance and changes in command settings has been manifested.

The outer speed loop in vector controlled PMSM drive greatly affects the drive performance. In order to combine the advantages of proportional plus integral (PI) and fuzzy controllers, hybrid fuzzy-PI controllers can be used in which the output can either be the outputs of the two, i.e. the PI or fuzzy units being switched as per the predetermined speed errors or be a combination of the two outputs with separate weights assigned to them with online calculations for the weights from the speed errors. In [23] Amit Vilas Sant and K. R. Rajagopal reported the vector control of PMSM with hybrid fuzzy-PI speed controller with switching functions calculated based on the weights for both the controller outputs using the output of only the fuzzy controller, only the PI controller or a combination of the outputs of both the controllers. These switching functions are very simple and effective and do not demand any extra computations to arrive at the hybrid fuzzy-PI controller outputs.

A new composite control strategy was proposed by Liye Song and Jishen Peng [24] for PMSM drives to achieve fast dynamic response and minimum steady state error. Based on the prior given the scope of the deviation, it implemented the automatically switch between fuzzy control and the PI control, and designed the control system model of permanent magnet synchronous motor. It has been found that the speed loop regulator realized by the fuzzy-PI control improves the respond speed of the system and also seen that the sudden addition of a load torque affects the speed respond of the PI regulator obviously but not the fuzzy-PI regulator. Fuzzy PI control system could precisely identify the change of the error and its change rate, could carry out responding switch adjustment on the supply quantity, could overcome oscillation effectively and could trace the load’s change precisely and timely.

The performance of the fuzzy logic controller (FLC) is better under transient conditions, while that of the proportional plus integral (PI) controller is superior near the steady-state condition. The combined advantages of these two controllers can be obtained with hybrid fuzzy-PI speed controller. The computations involved with the FLC are much higher as compared to that of the PI controller. FLC output is near the maximum permissible value at the beginning of a transient condition but reducing with the reduction in the speed error. Instead of the FLC, [25] presented a fuzzy equivalent proportional (FEP) controller was used along with the PI controller to make it a hybrid PI (HPI) controller which eventually is much faster and less computation intensive.

1.2. MOTIVATION:

Comprising with above mentioned many special features and characteristics of PMSM, it has been found very interesting subject matter for the present researchers. PMSM drive is largely maintenance free, which ensures the most efficient operation and it can be operated at improved power factor which can help in improving the overall system power factor and eliminating or reducing utility power factor penalties. From the research over PMSM until now it shows that, in future market PMSM drive could become an emerging competitor for the Induction motor drive in servo application and many industrial applications. So now there is a great challenge to improve the performance with accurate speed tracking and smooth torque output minimizing its ripple during transient as well as steady state condition such that it can meet the expectation of future market demand.

So looking out with such a motive, here a speed controller having superior performance for speed tracking has been designed as outer loop and a current controller which can provide smooth ripple less torque response has also been designed as inner loop for closed loop operation of the drive. Modelling and simulation is usually used in designing PM drives compared to building system prototypes because of the cost. Having selected all components, the simulation process can start to calculate steady state and dynamic performance and losses would have been obtained if the drive were actually constructed. This practice reduces time, cost of building prototypes and ensures that requirements are achieved. . So, Simulations have helped the process of developing new systems including motor drives, by reducing cost and which is done here in MATLAB/Simulink platform.

1.3. Objective:

The main objective of this research is to improve the performance of an IPMSM drive system by achieving more precise speed tracking and smooth torque response by implementing a Hybrid PI-FLC and an adaptive hysteresis band current controller respectively by employing their superior performance.

The overall objectives to be achieved in this study are:

- To design the equivalent d-q model of IPMSM for its vector control analysis and closed loop operation of drive system.
- Analysis and implementation of PI, Fuzzy and Hybrid PI-Fuzzy logic controller separately as outer speed loop in steady state and transient condition (step change in load and speed) in MATLAB/Simulink environment.
- Analysis and implementation of conventional hysteresis current controller and adaptive hysteresis band current controller as inner current controller in MATLAB/Simulink environment to compare their performances so as to consider better controller for our system application.

- Comparison of system performance using PI, Fuzzy and Hybrid PI-FLC separately as speed controller and adaptive hysteresis current controller as controller during steady state and transient condition in MATLAB/Simulink environment.

1.4. Dissertation organization:

The dissertation is organized as follows:

Chapter 1 introduces the background for this dissertation research, motivation and the research objectives along with comprehensive literature review in related areas is also given.

Chapter 2 includes the mathematical modelling of interior permanent-magnet synchronous machines in rotor reference frame. Moreover, basic vector control operation principles of PM synchronous machines are briefly discussed.

Chapter 3 includes brief analysis and design of different Speed and Current controllers which include PI, Fuzzy and Hybrid PI-FLC as speed controllers and conventional hysteresis and Adaptive hysteresis band controller as current controllers along with their advantages and disadvantages. Finally it describes the whole system operation by considering Hybrid PI-FLC and AHBCC as speed and current controller respectively for their superior performance.

Chapter 4 includes the simulation results. A comparative study of PI, Fuzzy and Hybrid PI-FLC used separately has been made showing their superior performance during transient and steady state period. Also a comparison study of conventional Hysteresis and adaptive Hysteresis current controllers has been made in terms of torque ripple, current error and switching frequency to achieve better current controller for required drive operation.

Finally, Chapter 5 presents general conclusions and recommendations for future work.

CHAPTER 2

Overview and Dynamic Modelling of IPM Drive System

This chapter deals with the description and design of dynamic mathematical model of the permanent magnet synchronous motors drive system for its vector control analysis before proceeding to design control and observation algorithms for them.

2.1. Permanent Magnet Synchronous Motor Drive System:

The motor drive consists of four main components, the PM motor, inverter, control unit and the position sensor. The components are connected as shown in Fig. 2.1.

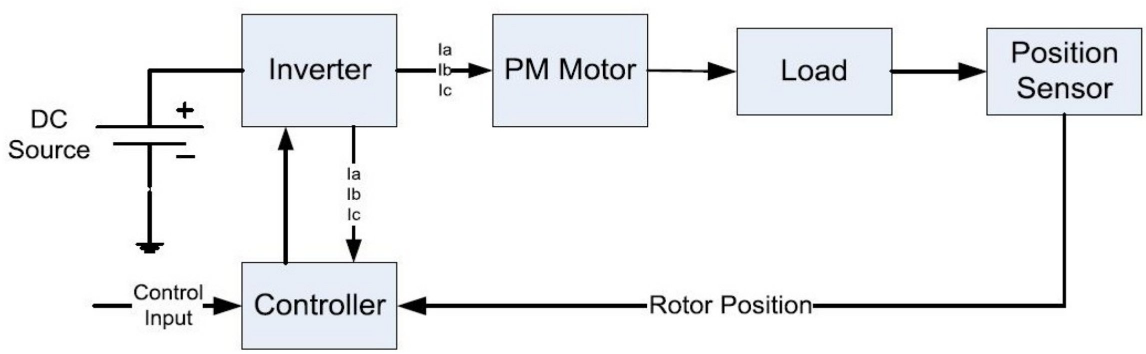


Fig.2.1: Schematic Block diagram for Drive System

2.2. Mathematical Model of IPMSM:

The mathematical model for the vector control of the PMSM can be derived from its dynamic d-q model which can be obtained from well-known model of the induction machine with the equation of damper winding and field current dynamics removed. The synchronously rotating rotor reference frame is chosen so the stator winding quantities are transformed to the synchronously rotating reference frame that is revolving at rotor speed.

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.

2) The induced EMF is sinusoidal.

3) Core losses are negligible.

4) There are no field current dynamics.

It is also be assumed that rotor flux is constant at a given operating point and concentrated along the d axis while there is zero flux along the q axis, an assumption similarly made in the derivation of indirect vector controlled induction motor drives [15].

The rotor reference frame is chosen because the position of the rotor magnets determine independently of the stator voltages and currents, the instantaneous induced emf and subsequently the stator currents and torque of the machine. When rotor references frame are considered, it means the equivalent q and d axis stator windings are transformed to the reference frames that are revolving at rotor speed. The consequences is that there is zero speed differential between the rotor and stator magnetic fields and the stator q and d axis windings have a fixed phase relationship with the rotor magnet axis which is the d axis in the modelling. The stator equations of the induction machine in the rotor reference frames using flux linkages are taken to derive the model of the IPMSM as shown in Fig.2.2:

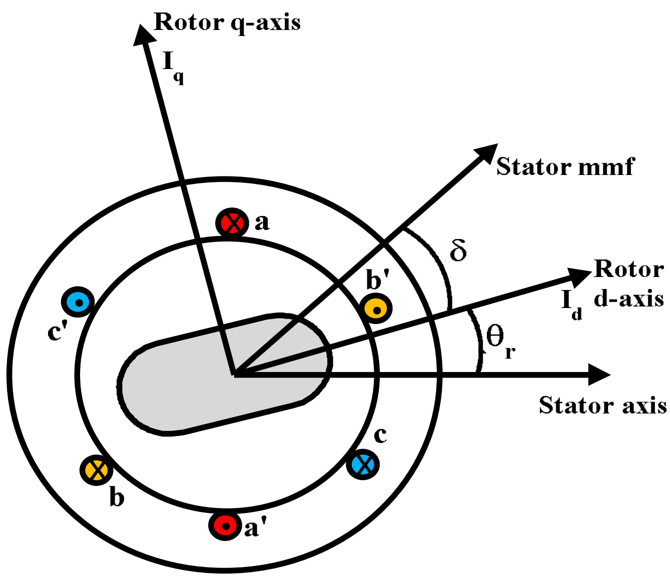


Fig.2.2: IPM machine synchronously rotating d-q reference frame.

So an IPM machine is described by the following set of general equations:

Voltage equations are given by:

$$V_d = R_s i_d - \omega_r \lambda_q + \frac{d\lambda_d}{dt} \tag{2.1}$$

$$V_q = R_s i_q + \omega_r \lambda_d + \frac{d\lambda_q}{dt} \tag{2.2}$$

Flux linkages are given by

$$\lambda_q = L_q i_q \tag{2.3}$$

$$\lambda_d = L_d i_d + \lambda_f \tag{2.4}$$

Substituting (2.3) & (2.4) into (2.1) & (2.2), we get

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \frac{d}{dt}(L_q i_q) \tag{2.5}$$

$$V_d = R_s i_d - \omega_r L_q i_q + \frac{d}{dt}(L_d i_d + \lambda_f) \tag{2.6}$$

Arranging equations (2.5) and (2.6) in matrix form

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \frac{dL_q}{dt} & \omega_r L_d \\ -\omega_r L_q & R_s + \frac{dL_d}{dt} \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \frac{d\lambda_f}{dt} \end{pmatrix} \tag{2.7}$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \tag{2.8}$$

$$T_e = \frac{3}{4}P\left[\lambda_f i_q + \left(L_d - L_q\right)i_q i_d\right] \tag{2.9}$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{2.10}$$

Solving for rotor mechanical speed from (2.10), we get

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \tag{2.11}$$

And rotor electrical speed is $\omega_r = \omega_m\left(\frac{P}{2}\right)$ (2.12)

2.2.1. Park Transformation and Dynamic d-q Modelling:

The dynamic d-q modelling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages and currents to dqo variables by using Parks transformation [16]. Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained:

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

In contrast, V_{dqo} can be converted to V_{abc} as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin\theta_r - 120 & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix}$$

2.2.2. Equivalent circuit of PMSM:

For analysis purpose equivalent circuits of the motors are used for study and simulation of motors. From the d-q modelling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation $\boldsymbol{\lambda_f = L_{dm} i_f}$, following figure can be obtained from [15] shown as fig 2.3 and fig.2.4.

The equivalent circuits are

1. Dynamic stator q-axis equivalent circuit

2. Dynamic stator d-axis equivalent circuit

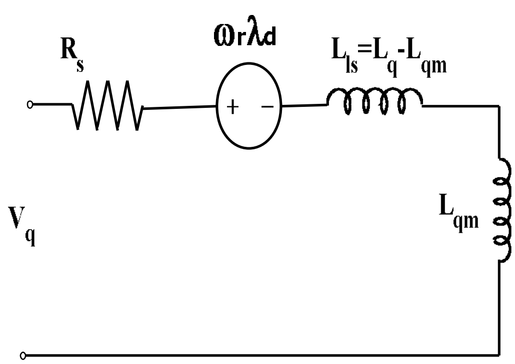


Fig.2.3: Stator q-axis equivalent circuit

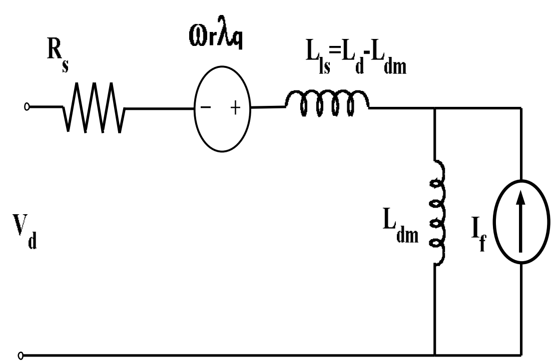


Fig.2.4: Stator d-axis equivalent circuit

2.3. Vector Control or Field Oriented Control Analysis:

This control strategy was developed prominently in the1980s to meet the challenges of transient condition analysis and oscillating flux with torque responses in inverter fed induction and synchronous motor drives during transient as well as steady state condition. The inexplicable dynamic behaviour of large current transients and the resulting failure of inverters was a curse and barrier to the entry of inverter fed ac drives into the market. Compared to these ac drives, the separately excited dc motor drives were excellent dynamic control of flux and torque. The key to the dc motor drives performance is its ability to independently control the flux and torque [15].

2.3.1. Derivation of Vector Control IPMSM Drive:

The vector control separates the torque and flux channels in the machine through its stator excitation inputs. The vector control for PMSM is very similar to the vector control of induction motor drives. In this section, the vector control of the three-phase PMSM is derived from its dynamic model. Considering the currents as inputs, the three-phase currents are:

$$i_a = i_s \sin\left(\omega_r t + \delta\right) \tag{2.13}$$

$$i_b = i_s \sin\left(\omega_r t + \delta - \frac{2\pi}{3}\right) \tag{2.14}$$

$$i_c = i_s \sin\left(\omega_r t + \delta + \frac{2\pi}{3}\right) \tag{2.15}$$

Where δ is the angle between the rotor field and stator current phasors.

The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed ω_r, using Park's transformation. The q and d axis Currents are constants in the rotor reference frames since δ is a constant for a given load torque. As these constants, they are similar to the armature and field currents in the separately excited dc machine. The q axis current is distinctly equivalent to the armature Current of the dc machine; the d axis current is field current, but not in its entirety. It is only a Partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. For this reason the q axis current is called the torque producing component of the stator current and the d axis current is called the flux producing component of the stator current.

Using park's transformation this stator current must be transformed to rotor reference frame

$$\begin{pmatrix} i_q \\ i_d \\ i_o \end{pmatrix} = \frac{2}{3}\begin{pmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} \tag{2.16}$$

Putting the equation (2.13), (2.14) and (2.15) in (2.16) and solving, then we get

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix} = (i_s)\begin{pmatrix} \sin\delta \\ \cos\delta \end{pmatrix} \tag{2.17}$$

Using equation (2.9) and (2.17) the electromagnetic torque is obtained as given below

$$T_e = \frac{3}{2}.\frac{P}{2}\left[\frac{1}{2}\left(L_d - L_q\right)i_s^2 \sin 2\delta + \lambda_f i_s \sin\delta\right] \tag{2.18}$$

In order to achieve dc motor like behaviour, the control needs knowledge of position of the instantaneous rotor flux or rotor position of PM motor. Knowing the position, the three phases current can be calculated.

Its calculation using the current matrix depends on the control desired.

a. Constant Torque Operation.

b. Flux weakening Operation.

These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and flux weakening starts as shown in fig.2.5.

a) Constant Torque Operation:

In this control strategy the d-axis current is kept zero, while the vector current is align with the q-axis in order to maintain the torque angle equal with 90^o. This is one of the most used control strategy because of the simplicity, especially for SPMSM. In case of IPMSM, with a high saliency ratio it is not recommended to use this control strategy because of the reluctance torque produced.

The torque equation can be rewritten as:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f .i_q \tag{2.19}$$

So

$$T_e = k_t . i_q \quad \text{Where, } \quad k_t = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f \qquad (2.20)$$

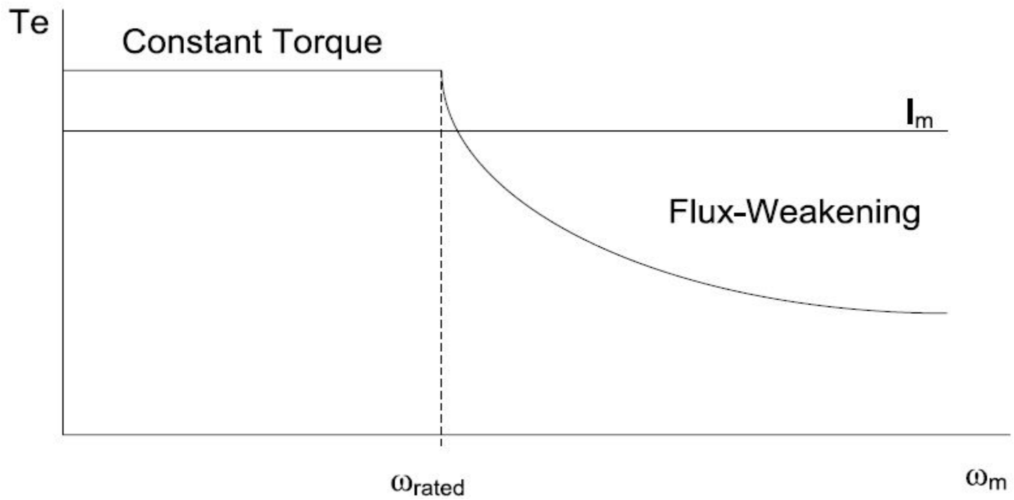


Fig.2.5 IPMSM characteristics in constant torque and field- weakening regions

Note that the torque equation (2.20) resembles with that of the dc machine where the torque is only dependent on quadrature axis current when we consider the field flux constant and hence provide its equivalent operation.

2.4. Summary:

In this chapter, mathematical models of PM machines are derived in the rotor reference frame with respect to the rotor of PM motors with saliency. By using the Park's transformation, all time-varying inductances in the voltage equations are eliminated and in turn the models are simplified and vector control algorithms can be implemented. Dynamic stator d and q-axis equivalent circuit of motor are derived using stator voltage equations**.** Finally Constant-torque operation is derived for an IPMSM drive system.

CHAPTER 3

Implementation of Current and Speed Controllers

3.1 Current Controllers:

The behaviour of proposed PMSM drive system predominantly depends on the characteristics of type of current control technique that we employ for the current control of Voltage Source Inverter (VSI). So, the current control of VSI is again another subject that we have to concern seriously for better performance of motion control drive applications. In this proposed system, the current controller has implemented in inner loop which generates the control gate signals for control of inverter output which in spite control output torque of IPMSM. Appropriate selection of controllable switches and current controller play an important role for the better efficacy of the VSI as well as drive system.

Now going through the characteristics of various controllers that have been previously used as current controller for the speed control of IPMSM drive [5-7] [11], it has been found that Adaptive Hysteresis Band Current Controller (AHBCC) can be used to achieve a better and satisfying control for the current controller. Although fixed band hysteresis current controller is simple in implementation with less complexity but prior to it AHBCC has been preferred due to its some advantages over fixed band hysteresis current controller. So in this section, conventional fixed band hysteresis and adaptive hysteresis band current control technique has been discussed along with their design and implementation of adaptive hysteresis band current controller in the drive system.

3.1.1. Hysteresis Current Controller:

Among the different PWM techniques, hysteresis-band current control PWM technique is popularly used due of its simplicity of implementation. Hysteresis band current controller is a current control technique in which controller will try to keep the input current error within a range which is fixed by some width of band gap defined by upper and lower band. In this technique, the reference current of any phase is summed with the negative of the measured current value of that phase which will give the current error. The current error is then provided as the input of the controller which then compare it with its defined fixed band and gives the output as per its characteristics as required gate drive signal. The characteristics of hysteresis band can be defined as "when the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg (one at a time) is turned ON and when the current attempts to become more than the upper limit of band, the bottom switch (one at a time) is turned ON" [4] [5] [15]. So, the switching logic can be formulated as follows:

Suppose current error (δ) is given by,

δ = Reference Current (I_{ref}) – Actual current (I_{act}), then

- If δ >HB upper switch of any single leg of VSI is ON (say Q_1=1) and lower switch of same leg is OFF (say Q_4=0).
- If δ <-HB upper switch of any single leg of VSI is OFF (say Q_1=0) and lower switch of same leg is ON (say Q_4=1).

For symmetrical operation of three phases, above logic is same but only band profile of other phases will be displaced with 120^0.

The logic based upon which this controller generates the required gate drive signal can be easily understood from fig. 3.1 and fig. 3.2

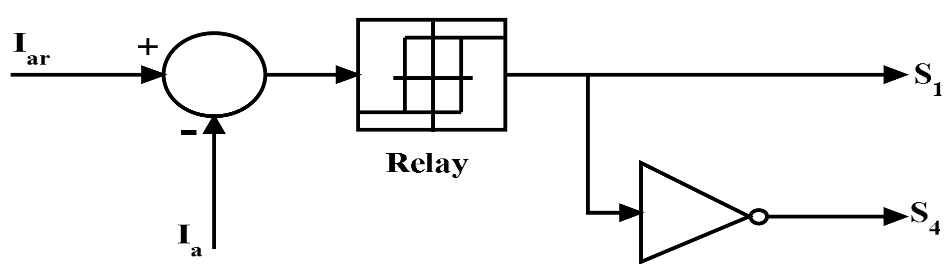


Fig.3.1: Schematic diagram of Hysteresis controller.

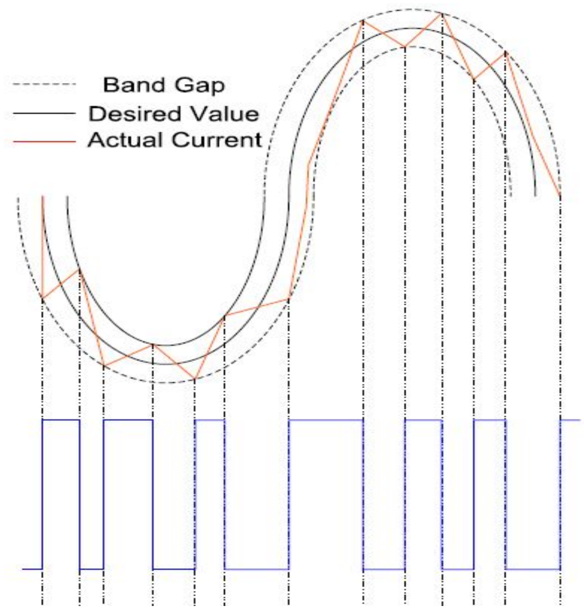


Fig 3.2: Hysteresis Controller Operation

Here we can observe that the current error has restricted in between the defined band gap which in other view trying to follow the reference current with less current error which we can achieve by decreasing the defined band gap and as a result it producing the required gate drive signal as per its behaviour. But on the other hand we also have to take care of better performance of drive system during fixing up the upper and lower hysteresis band such that it should be optimum and it would not lead to poor operation of drive system.

3.1.1.1 Advantages of fixed Band Hysteresis current controller:

The conventional fixed band hysteresis current control technique has been suitable for current controlled voltage source inverters due to some of its advantages as follows:

1. Simple implementation.
2. Inherent current peak limitation.
3. Good transient response.
4. Unconditioned stability.
5. Robust against system parameters variation.

3.1.1.2. Disadvantages of fixed Band Hysteresis current controller:

Despite of above advantages of the fixed band hysteresis band current control, there are some unavoidable drawbacks in the technique as follows:

1. Switching frequency is not constant i.e. variable switching frequency.
2. Greater current ripple in steady- state.
3. The modulation process generates undesired sub-harmonic components resulting in higher machine heating.
4. No intercommunication between each hysteresis controller of other phases and hence no strategy to generate zero-voltage vectors. Due to which the switching frequency increases at lower modulation index and the signal will leave the hysteresis band whenever the zero vector is turned on.

3.1.2. Adaptive Hysteresis Band Current Controller:

The problem of fixed band hysteresis current controller can be alleviated by a novel adaptive hysteresis band current control technique where the band is a function of variation in load current, switching frequency (f_s), counter emf (v_f) and slope of reference current (m) [7]. Due to such controlled behaviour of adaptive hysteresis band current controller we can get more accurate, ripple less and better performance of IPMSM drive system than fixed band hysteresis current controller.

3.1.2.1 Analysis for modelling of Adaptive Hysteresis Band Current Controller:

An adaptive hysteresis-band for adaptive hysteresis current controller can be modelled such that the band is modulated with the system parameters to maintain the modulation frequency to be nearly constant. Although this strategy is applicable to general ac drives as well as other loads, an interior permanent magnet synchronous machine load is considered here. Systematic analytical expressions of the hysteresis band has been derived as functions of system parameters with an IPM machine drive system and a voltage-fed current-controlled PWM inverter connected to it.

Generally IPMSM machine drive can be operated in the following three modes

1. Neutral Connected with Pure Inductance Load
2. Neutral Connected with Counter emf Load
3. Isolated Neutral with Counter emf Load

But isolated neutral with counter emf load is the most practical case as compared to other two modes of operation. So for designing of adaptive hysteresis band, here the third case is taken into consideration [6].

With the isolated neutral, the machine phase voltages interact with each other and no longer be $0.5v_{dc}$ as like when neutral is connected as shown in fig.3.3.When Q_1 is ON , the possible phase-a voltage may be 0, 1/3, $2/3V_{dc}$, and when Q_4 is ON, the corresponding voltage may be 0,-1/3, $-2/3V_{dc}$. Typical PWM phase voltage and current waves during a modulation cycle are shown in fig.3.4. With the assumed polarity of counter emf when Q_1 is ON, the phase current in a time segment will rise or fall, respectively, depending on the dominating phase voltage or counter emf, but the current will always fall during the Q_4-ON period.

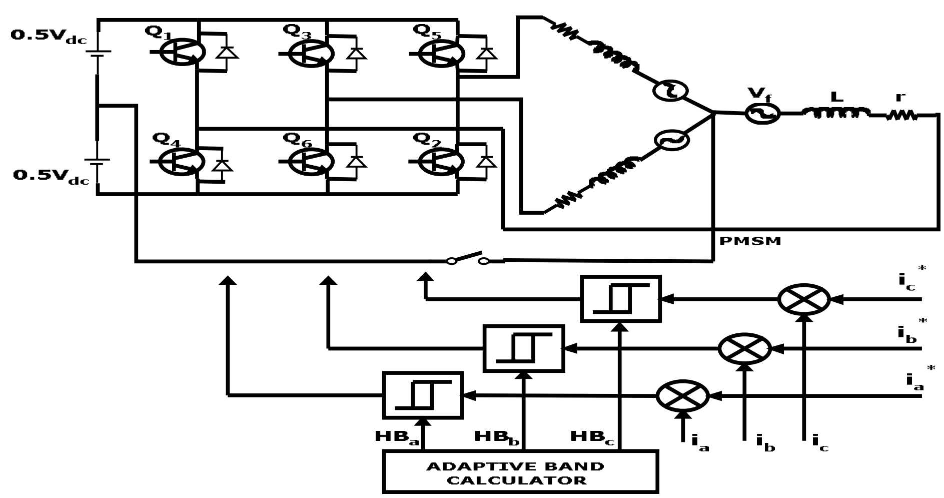


Fig.3.3: Adaptive Current controlled IPMSM drive system

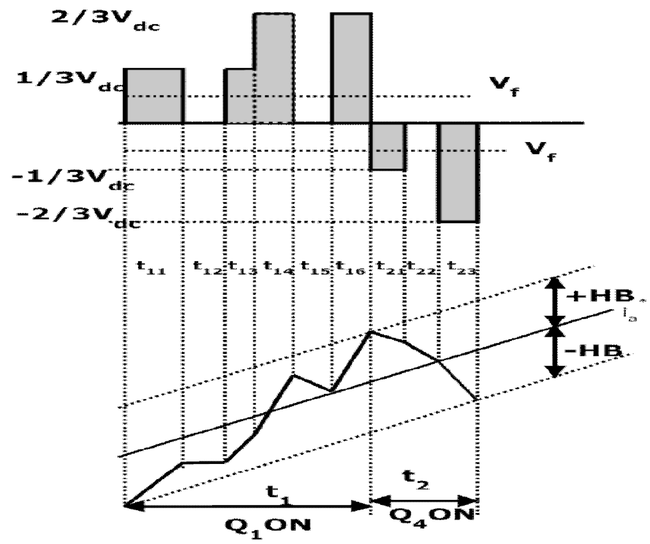


Fig.3.4: Typical PWM voltage and current waveform with
Calculation of Hysteresis-band

The general expression of incremental current rise ΔHB during Q_1 – ON period is given by:

$$\Delta HB = t_{1n}\frac{di_a^+}{dt} - t_{1n}\frac{di_a^*}{dt} \tag{3.1}$$

But from the IPMSM drive system we can have

$$\frac{di_a^+}{dt} = \frac{1}{L}\left(aV_{dc} - v_f\right) \tag{3.2}$$

Where a= 0, 1/3 or 2/3 & for simplicity let m= $\frac{d\,i_a^*}{d\,t}$

Hence, $$\Delta HB = t_{1n}\frac{1}{L}\left(aV_{dc} - v_f\right) - t_{1n}m \tag{3.3}$$

So summing up the total current, we can get

$$2HB = \sum\Delta HB = \sum\left[-t_{1n}\left(m + \frac{v_f}{L}\right) + \frac{1}{L}t_{1n}aV_{dc}\right]$$

$$= \left[-t_1\left(m + \frac{v_f}{L}\right) + \frac{1}{L}\sum t_{1n}aV_{dc}\right] \tag{3.4}$$

Similarly, the general expression of incremental current fall during the Q_4 – ON period is given by

$$-\Delta HB = t_{2n}\frac{di_a^-}{dt} - t_{2n}\frac{di_a^*}{dt} \tag{3.5}$$

But in this case

$$\frac{di_a^-}{dt} = -\frac{1}{L}\left(aV_{dc} + v_f\right) \tag{3.6}$$

Hence

$$-\Delta HB = -\frac{t_{2n}}{L}\left(aV_{dc} + v_f\right) - t_{2n}m \tag{3.7}$$

So, the total current fall can be obtained as

$$\begin{aligned} -2HB &= \sum(-\Delta HB) = \sum\left[-t_{2n}\left(m + \frac{v_f}{L}\right) - \frac{1}{L}t_{2n}aV_{dc}\right] \\ &= \left[-t_2\left(m + \frac{v_f}{L}\right) - \frac{1}{L}\sum t_{2n}aV_{dc}\right] \end{aligned} \tag{3.8}$$

Where t1& t_2 is the average current rise and fall duration respectively

In equation (3.4) and (3.8), the second term can be expressed as

$$\sum t_{1n}aV_{dc} = t_1 a' V_{dc} \tag{3.9}$$

$$\sum t_{2n}aV_{dc} = t_2 a'' V_{dc} \tag{3.10}$$

or

$$a' = \frac{\sum t_{1n}a}{t_1} \tag{3.11}$$

$$a'' = \frac{\sum t_{2n}a}{t_2} \tag{3.12}$$

Where a' and a'' are the respective applied voltage coefficients. Although the average applied voltages in the two intervals may have some asymmetry, still we can assume a'= a'' for simplicity. The parameters a' and a'' are typically varies between “1/3 and 2/3”.

Adding equation (3.4) & (3.8), we get

$$0=\frac{-1}{f_s}\left(m+\frac{v_f}{L}\right)+\frac{a'V_{dc}}{L}\left(t_1-t_2\right) \tag{3.13}$$

Where $t_1+t_2=\frac{1}{fs}$, f_s is switching frequency

So,

$$\left(t_1-t_2\right)=\frac{L}{f_s a'V_{dc}}\left(m+\frac{v_f}{L}\right) \tag{3.14}$$

Now subtract equation (3.8) from (3.4), we get

$$4HB=\left(m+\frac{v_f}{L}\right)\left(t_2-t_1\right)+\frac{a'V_{dc}}{Lf_s} \tag{3.15}$$

Putting the equation (3.14) in (3.15) and solving, we get

$$HB=0.25\frac{a'V_{dc}}{Lf_s}\left[1-\frac{L^2}{a'^2V_{dc}^2}\left(m+\frac{v_f}{L}\right)^2\right] \tag{3.16}$$

The switching logic will be same as mentioned earlier for conventional hysteresis current controller and for the symmetrical operation of three phases, it is expected that the band profiles of all the phases will be same but phase will be displaced with 120^0. The adaptive hysteresis band can be modelled in MATLAB/Simulink is shown in fig.3.3:

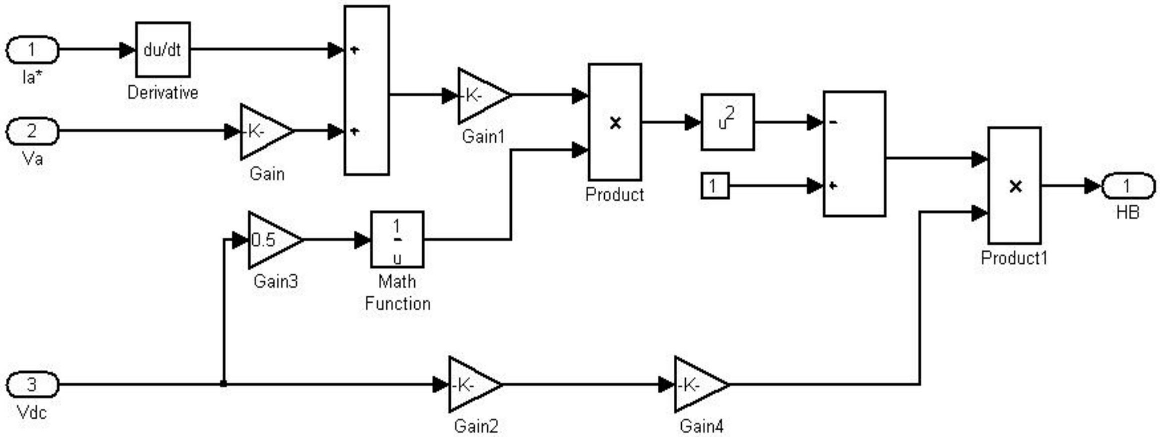


Fig. 3.5: The adaptive hysteresis bandwidth calculation block

3.2. Speed Controllers:

The design of the speed controller is important from the point of view of imparting desired transient and steady-state characteristics to the speed-controlled PMSM drive system. The purpose of a motor speed controller is to take a signal representing the demanded speed, and to drive a motor at that speed.

3.2.1. PI Controller:

A proportional plus integral controller is sufficient for many industrial applications and hence, it is considered in this section. The speed error between the speed and its reference, given by (ω_r^*- ω_r), is processed through a proportional plus integral (PI) type controller (hereafter known as the speed controller) to nullify the steady-state error in speed. The output of this speed controller constitutes the electromagnetic torque reference, *T**, because the speed error can be nulled and minimized only by increasing or decreasing the electromagnetic torque in the machine, depending on whether the speed error is positive or negative, respectively.

The operation of the controller must be according to the speed range. For operation up to rated speed it will operate in constant torque region and for speeds above rated speed it will operate in flux-weakening region. In this region the d-axis flux and the developed torque are reduced.

Speed controller calculates the difference between the reference speed and the actual speed producing an error, which is fed to the PI controller. PI controllers are used widely for motion control systems. They consist of a proportional gain that produces an output proportional to the input error and an integration gain to minimize the steady state error zero for a step change in the input. The design of the speed loop assumes that the current loop is at least 10 times faster than speed loop. The PI controller can be integrated as outer speed loop in system is shown in fig.3.6.

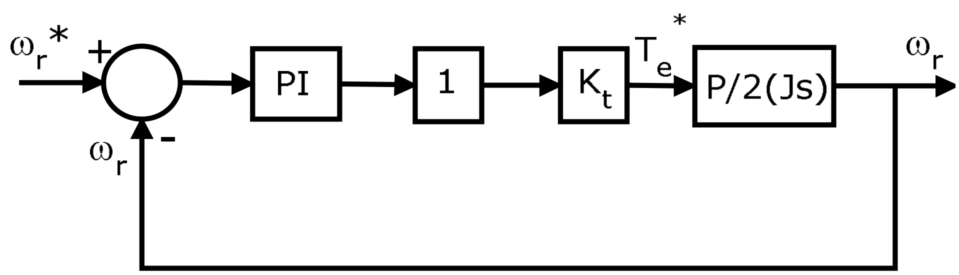


Fig.3.6: Block diagram of speed loop

For our IPMSM; k_t = (3/2) (P/2) λ_f = 0.816; where: λ_f = 0.272; P = 4; J = 0.000179

3.2.2. Fuzzy Logic Controller:

The concept of "Fuzzy Logic" was first introduced by Lotfi A. Zadeh in 1965 with a novel proposal of Fuzzy Set Theory. Fuzzy logics had been studied since the 1920s as infinite-valued logics notably by Łukasiewicz and Tarski. Fuzzy logic theory is an artificial intelligence method which has been has been employed to many fields like control theory to artificial intelligence.

Fuzzy Logic is a form of many-valued logic; it deals with reasoning value that is approximate rather than fixed and exact value. Compared to traditional binary sets (where variables may take on true or false values) fuzzy logic variables that may have a value ranges with some degree between 0 and 1. On other hand when linguistic variables are used with some reasonable degrees may be managed by specific functions called as **Membership Function**. The **Membership Function** of a fuzzy set is a generalization of the indicator function in classical sets. In fuzzy logic, it signifies the degree of truth as an extension of valuation. For any set X, a membership function on X is any function from X to the real unit interval [0, 1].

A **Fuzzy Logic Control System** is a control system based on fuzzy logic "a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1 and gives the requisite response according to the defined rules, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0 (true or false, respectively)".

Among the various intelligent controllers, fuzzy logic controller (FLC) is the simplest , robust and better than others in terms of quick response time, also insensitivity to parameter and load variations etc [17-19]. Thus, here a FLC is implemented as another speed controller for proposed vector control of IPMSM drive and also to study the performance comparison of the proposed IPMSM drive with conventional PI controller based drive in MATLAB/Simulink environment.

The outer speed loop in vector control greatly affects the system performance. Proportional plus integral (PI) controllers are usually preferred, but because of its fixed proportional gain constant and integral time constant, the behaviour of the PI controllers are affected by parameter variations, load disturbances and speed fluctuation. Conventional PI controller also suffers from overshoot and undershoots of response, when some unknown nonlinearities or noise are present in system [23].

These problems can be overcome by the fuzzy logic controllers [20], which do not require any mathematical model and are based on the linguistic control law obtained from the experience of the system operator. Also the problem of overshoot and undershoot during transient condition can be alleviate by FLC [21-22]. The Fuzzy Logic Controller (FLC) is the rule based, non-linear controller which takes the analog inputs and analyses it by converting it to logical variables and gives the output by defuzzification. In this case we are considering the speed error (e) and change in speed error as inputs for the controller. But the performance of the fuzzy controller as compared to the PI controller is superior mainly under transient conditions.

The fuzzy logic controller can be shown by a block diagram as fig.3.7:

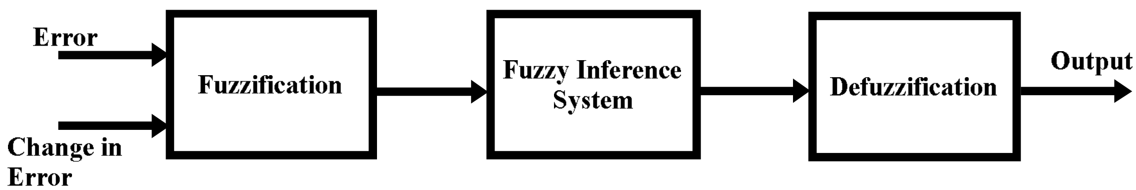


Fig.3.7: Block diagram for designing of FLC

It consists of blocks as:

- ❖ Fuzzification
- ❖ Fuzzy Inference System (FIS)
- ❖ Defuzzification

❖ **Fuzzification:** It is the process of conversion of inputs analog variables to linguistic variables (fuzzy numbers).

❖ **Fuzzy Inference System (FIS):** It is a popular computing framework based on the concepts of fuzzy theory, fuzzy **If-Then** rules and fuzzy reasoning. It is also known as fuzzy rule based system or fuzzy expert system.

Basically FIS consists of three main components: a rule base, which provides a selection of rules; a data base, which specify the membership functions used in the fuzzy rules; and a reasoning mechanism, which executes the inference procedure upon the rules and given facts to produce a reasonable output. The basic FIS can take fuzzy singletons and produces the outputs almost always as fuzzy sets. Sometimes it is necessary to have a crisp output, especially in a situation where a FIS is used as a controller. Therefore, we require a method of defuzzification to extract a crisp value that best represents a fuzzy set.

- **Defuzzification:** In Contrast to fuzzification it is simply the process of converting fuzzy nature output value to crisp value.

So the whole system consists of Fuzzification, FIS and defuzzification of FLC which can be shown in fig. 3.8:

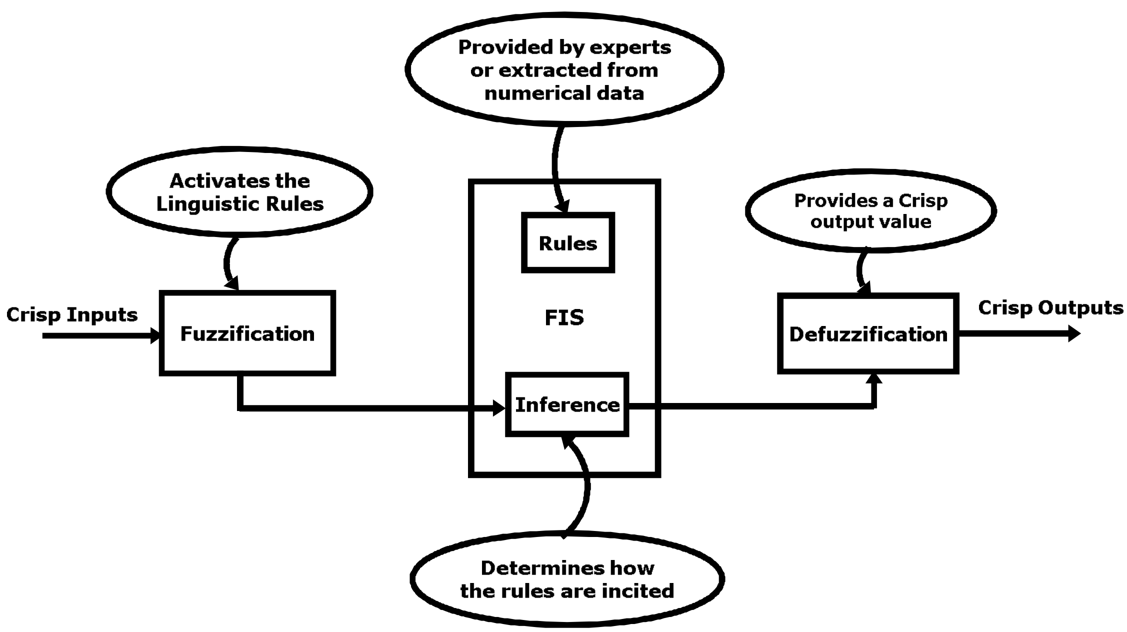


Fig. 3.8: Block diagram of FLC showing detail logic of different components

The Fuzzy Logic Controller initially encodes the crisp error and change in error variables into fuzzy variables and then it's mapped into linguistic variable. Membership functions are associated with inputs and output variables as shown in fig.3.9 which here we have taken as Triangular membership functions consists of two inputs and one output.

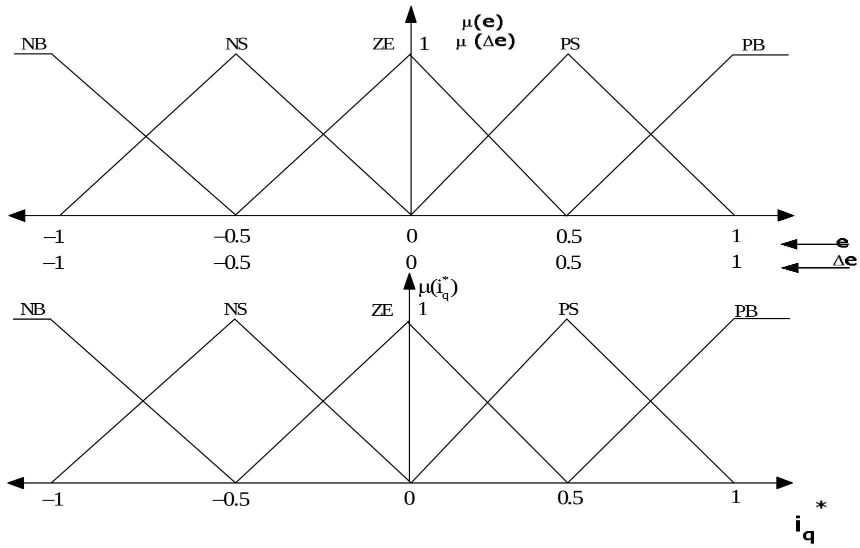


Fig.3.9: The fuzzy membership functions of input variables as speed error (e), change in speed error (Δe) , and output variable as reference q-axis current (i_q^*).

For the designed FLC, the speed error (e) and change of speed error (Δe) are taken as input variables and the output variable is command q-axis current i_q. The d-axis current i_d is set to zero for desired speed operation i.e. below rated speed. The membership function for i_q is designed in such as a way that the motor can generate the necessary torque to follow the given reference speed and load torque as quickly as possible. This can be done based on the knowledge of operation on fuzzy logic and motor control. Here, the ranges of Membership function for i_q is selected by trial and error in such a way that the motor generates rated torque at rated condition. Similarly, the selection of membership function at the input side of the FLC depends on the rated speed of the motor chosen by trial and error method so that we can obtained a better tracking of commanded speed.

Now there are mainly two types of Fuzzy Inference System which are used for evaluation of individual rules. The difference between two fuzzy inference systems based on their fuzzy rules and their aggregation. These two types of FIS are:

1. Mamdani **Max-Min** composition scheme
2. Mamdani **Max-Prod** composition scheme

1. Mamdani **Max-Min** composition scheme**:** In this scheme aggregation used is Maximum operation and implication is Minimum operation.
2. Mamdani **Max-Prod** composition scheme: In this scheme aggregation used is Maximum operation and implication is Product operation.

Here in this FLC, a rule base is defined to control the output variable. This fuzzy rule is a simple IF-THEN rule with some condition and conclusion which relates the input variables to the required output variables properties. The FLC converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by an expert knowledge and human experience with understanding. Initially, the speed error 'e' and the rate of change in speed error 'Δe' have been placed as input variables of the FLC. Then the output variable of the FLC generates the controlled q-axis reference current i_q^*. The fuzzy rules are expressed in English like language with syntax such as, **If** {error speed 'e' is X and rate of change of error speed 'Δe' is Y} **then** {control output variable $i_q^*$is Z}. To convert these numerical variables into linguistic variables, here the following five fuzzy levels or sets has been chosen as: NB (Negative big), NS (Negative small), ZE (Zero), PS (Positive small), and PB (positive big) are used and summarized in Table 1. Each of the inputs and the output contain membership functions with all these three linguistics with 5*5 Triangular MFs.

TABLE 1. FUZZY LOGIC CONTROL RULES

E \ Δe	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

The mapping of the fuzzy inputs into the required output is derived with the help of a rule base as given in Table 1.Each rule of the FLC is defined with an **If** part called the antecedent, and with a **then** part called the subsequent. The antecedent of a rule contains a set of conditions and the subsequent contains a set of conclusions. So “If the conditions of the antecedents are satisfied, then the conclusions of the subsequent will be applied”.

Finally the output consequences will be fuzzy in nature and has to be converted into a crisp value by using any Defuzzification technique. A schematic model of the FLC is shown in fig.3.10:

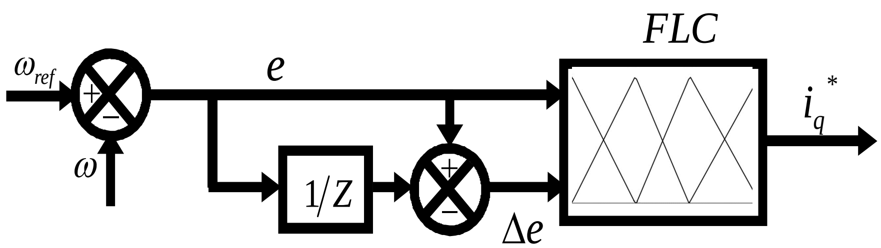


Fig.3.10**:** Schematic model of fuzzy logic controller

So for the proposed system, Type-1Fuzzy Logic controller has been chosen along with its following characteristics:

- Triangular based 5×5 Membership Function [MF] for both inputs as well as output variables of FLC.
- Fuzzy implication using Mamdani’s **min** operators.
- Defuzzification using **Centroid** method for getting required output from the FLC.

3.2.3. Hybrid PI-Fuzzy Logic Controller (PI-FLC):

As it is important to achieve a smooth and improved performance of outer speed loop in vector controlled PMSM drive during transient as well as steady state condition, the combined advantages of proportional plus integral (PI) and fuzzy controllers were selected and a Hybrid PI-Fuzzy controllers are designed in which the output can either be the outputs of the two, i.e. the PI or fuzzy units being switched during a particular period as per the predetermined speed errors.

PI controller has rarely superior performance as compared to the fuzzy controller under steady state conditions when speed error is very less while the FLC has superior performance mainly under transient condition and sometimes steady state condition also. So combining the superior performances of the fuzzy and PI controllers, a hybrid PI-fuzzy controller can be obtained. This can be implemented as an outer speed controller where the PI controller is rarely active near steady state conditions when the speed error found to be very less and the fuzzy controller is active during transient conditions and when the speed error is greater than some minimum predefined value. Hybrid PI-Fuzzy speed controller has been used for the control of the induction motor, where the fuzzy controller is active during speed overshoot or undershoot only [26].Alike in a permanent magnet brushless dc (PMBLDC) motor or PMSM also Hybrid PI-Fuzzy speed controller can be implemented where the fuzzy logic controller is activated under the condition of overshoot and oscillations, otherwise the output of the fuzzy logic controller is null and hence inactive and in contrast, the PI controller is activated during steady state condition with very less error. Here, the selection between the fuzzy and the PI speed controllers is carried through a logical switch which is based on a set of simple rules; oscillations have to be detected by comparing the sum of errors over a period of time with the sum of absolute errors over the same period. A schematic model which can describe the function of Hybrid PI-Fuzzy speed controller is shown in fig.3.11:

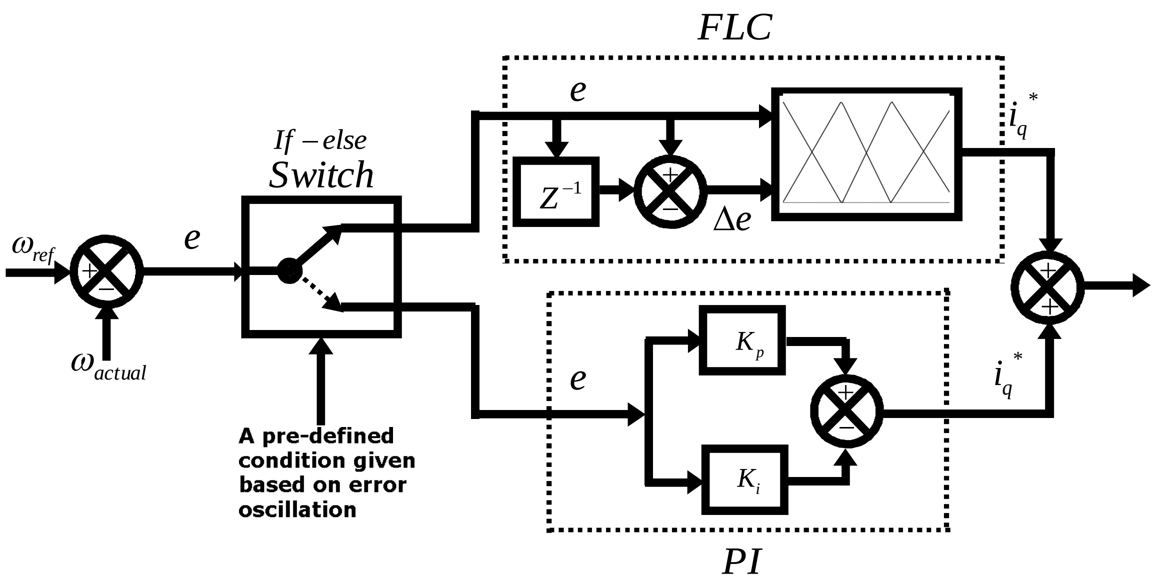


Fig.3.11: Schematic model of Hybrid PI-Fuzzy speed controller

The actual motor speed is sensed and compared with the commanded reference speed value. The speed error is processed by the hybrid PI-Fuzzy speed controller, where the FLC and PI controller are operated through a conditional switch and either of one from two controllers performs its function during a particular period which determines the reference value of the q-axis current. The condition that is provided to the conditional switch is set from the knowledge of speed error oscillation or rate of change in speed error that we can measure from our system response such that during the transient conditions the output of the fuzzy logic controller has the prominent effect on the output of the hybrid controller and during the steady state conditions with very less error, the PI controller will have the prominent effect. The condition for the conditional switch should be set as a "minimum" value of Δe such that the FLC will switch mainly when Δe will greater than a minimum set value of Δe which will mostly occurs under transient periods and PI controller will rarely switch when Δe will less than that minimum set value of Δe that is during steady state periods with very less speed ripple.

So, for comparative analysis of behaviour of conventional PI controller, FLC and Hybrid PI-Fuzzy controller, we designed the whole IPMSM drive system in MATLAB/Simulink environment and all three controllers were implemented separately as outer speed loop. The result and comparison of performance of these controllers were presented and analyses in later chapter where we can distinguish between their performances during different conditions and accordingly we can select our required controller as per our requirement and whole condition of drive system operation.

3.3. Description of Proposed Model:

After analyzing the performances of different current and speed controllers, Hybrid PI-FLC integrated as speed controller and Adaptive hysteresis band current controller integrated as current controller to achieve better performance for the designed PMSM drive system. The block diagram of proposed PMSM drive system based on Hybrid PI-FLC and AHBCC is shown in fig.3.12:

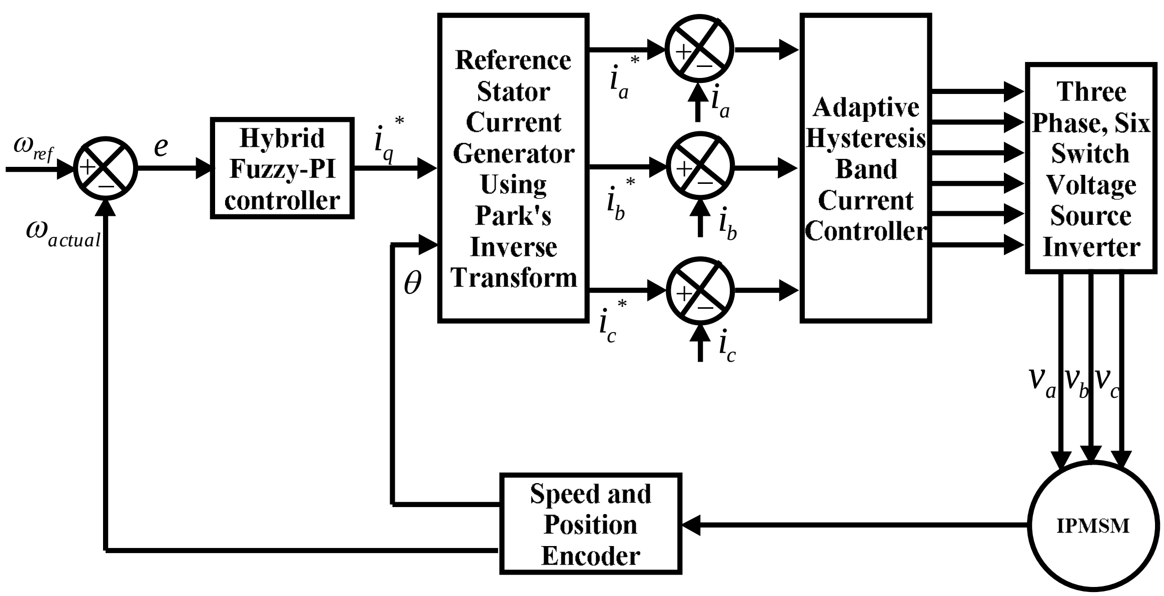


Fig.3.12: Block diagram of proposed PMSM drive system using Hybrid PI-FLC and AHBCC.

Fig. 3.12 shows the schematic diagram of a vector controlled IPMSM drive system with Hybrid PI-FLC controller as speed controller in the outer loop and an Adaptive

Hysteresis Band Current Controller (AHBCC) as current controller in the inner loop. The actual speed is compared with the reference speed and error speed (e) fed to the hybrid PI-FLC controller which gives reference torque component of current iq* . A conditional If-else switch is used inside Hybrid PI-FLC to select either FLC or PI controller to function as speed controller during a particular period according to preset change in speed error (Δe) value. Now using Inverse Park's transformation, the stator reference current is generated from iq* considering id*=0. The actual currents are sensed and compared with the generated references current and the error current are fed to the current controller which will generate the required gate drive signal such a way that it will results a ripple less smooth performance for IPMSM drive system.

3.4. Summary:

In this chapter some current controllers such as Conventional fixed band hysteresis current controller and adaptive hysteresis band current controller has been discussed along with their mathematical model. Their advantages and disadvantages were also discussed. Further some speed controller such as PI, FLC and Hybrid PI-FLC also discussed along with their designing. Their performances under different condition also analyzed. Finally description about proposed model with its block diagram and operation has been described.

CHAPTER 4

Simulation Results and Discussion

The conventional and proposed MATLAB/Simulink models were developed for 2.5 kW PMSM and the rest system parameters values are tabulated in Appendix A. The motor is operated in constant torque mode. In the designed model for performance improvement of IPMSM drive system, two controllers have been integrated: One as outer speed controller and other as inner current controller. Here our main aim is to analyze and compare the performances of PI, Fuzzy and Hybrid PI-FLC as different speed controllers but before that we require to select an excellent current controller which can provide smooth and ripple free responses of current and torque developed. So for selection of current controller first we compares the responses of drive system using conventional hysteresis current controller and Adaptive hysteresis band current controller and based on their performance we choose the better current controller for required operation of PMSM drive system. For this purpose PI controller is used as speed controller tuning its constants K_p= 0.3580 & K_i= 129.9014.

4.1. Performance Comparison of Current Controllers:

In this section, performance of Conventional hysteresis current controller and Adaptive hysteresis band current controller for the proposed drive system during steady state and transient condition (i.e. with variable load) simulated in MATLAB/Simulink has been presented. Simulation results are given at electrical speeds of 200 rad/sec.

4.1.1 Result during Steady State for Conventional Hysteresis Current Controller:

Here reference speed is 200 rad/sec and applied step Load torque = 1 N-m for $t \geq 0$. The fixed hysteresis band for the controller is set as ± 0.2. The motor speed response shown in fig. 4.1.1 (a) which shows the actual stator current obtained using park's inverse transformation. The torque developed (T_e) by the motor is shown in fig.4.1.1 (b) where T_e

reaches steady state value at less than 5 msec, but the torque ripple is larger. Fig. 4.1.1 (c) shows the speed response where the controller tracking the reference speeds within 15 msec.

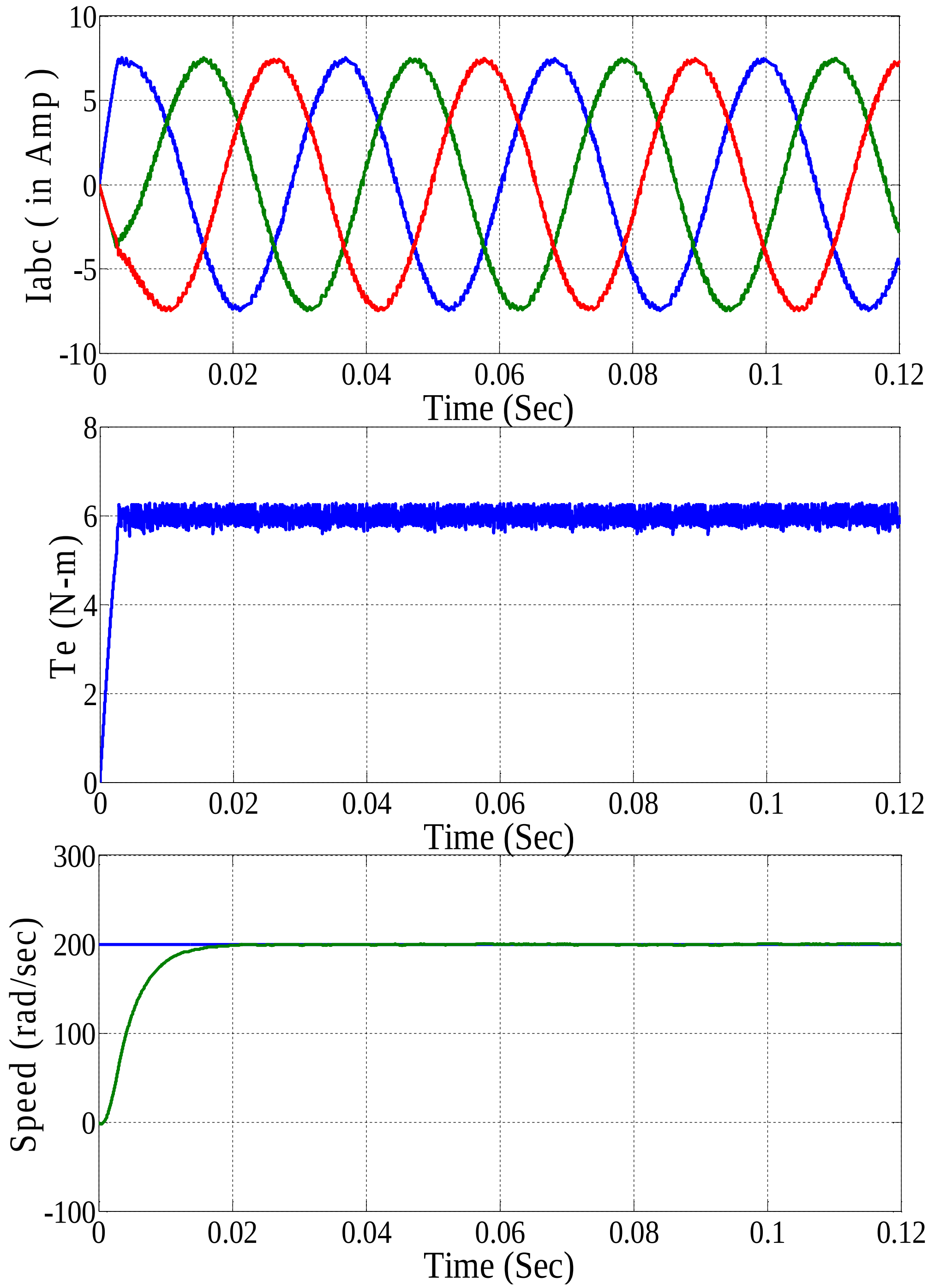


Fig.4.1.1 (a) Actual stator current waveform; (b) Response of developed torque; (c) Response of speed during steady state conditions using CHCC.

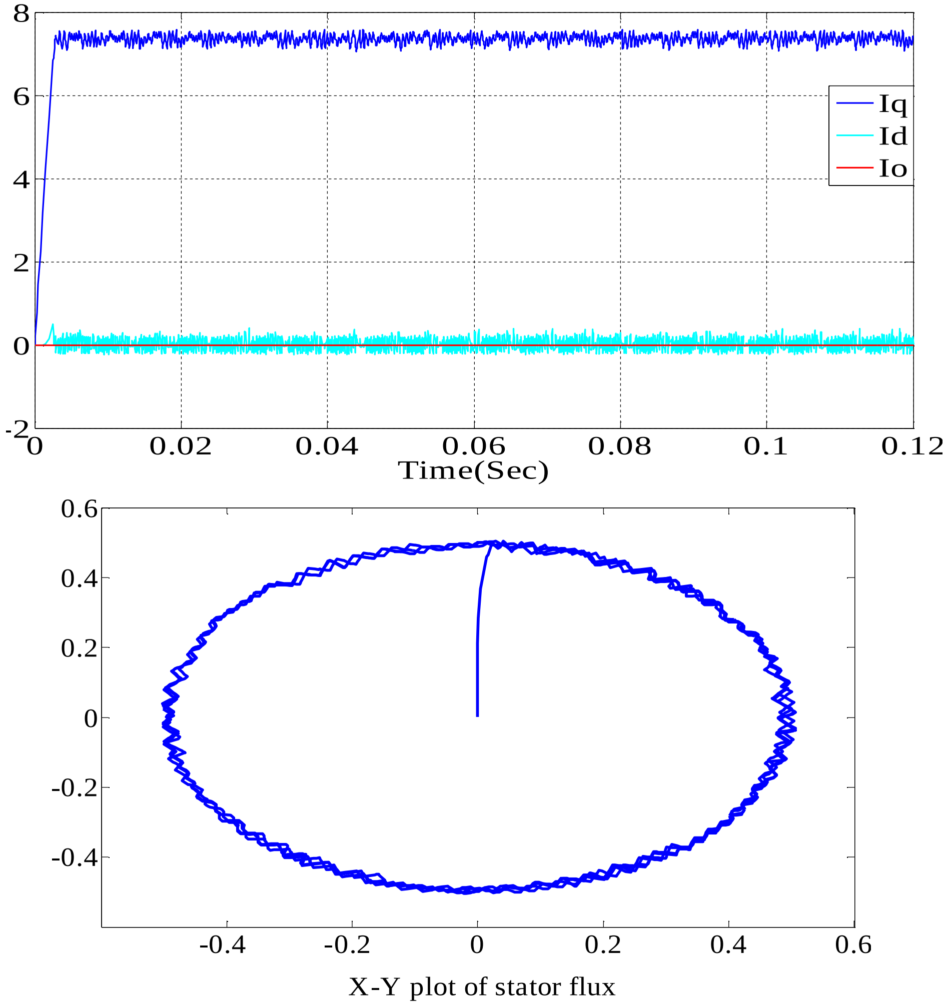


Fig.4.1.1 (d). d-q component of current ; (e) Response of stator flux during steady state conditions using CHCC

The corresponding d-q component of current is shown in fig.4.1.1 (d) in which i_d=0 due to constant torque mode of operation and i_q is responsible for T_e and fig.4.1.1 (e) shows the variation of stator flux in x-y plot containing large amount of ripples due to fixed band.

4.1.2. Result during Steady State for Adaptive Hysteresis Band Current Controller:

Implementing the Adaptive hysteresis current controller and keeping speed remains at commanding speeds. It can be clearly observed from the fig 4.1.2 (a) & 4.1.2 (b) i.e. waveforms of three phase stator current and electro-magnetic torque is very smooth with drastically reduction of ripples contents. Similarly the speed response shown in fig. 4.1.2 (c) is also smooth.

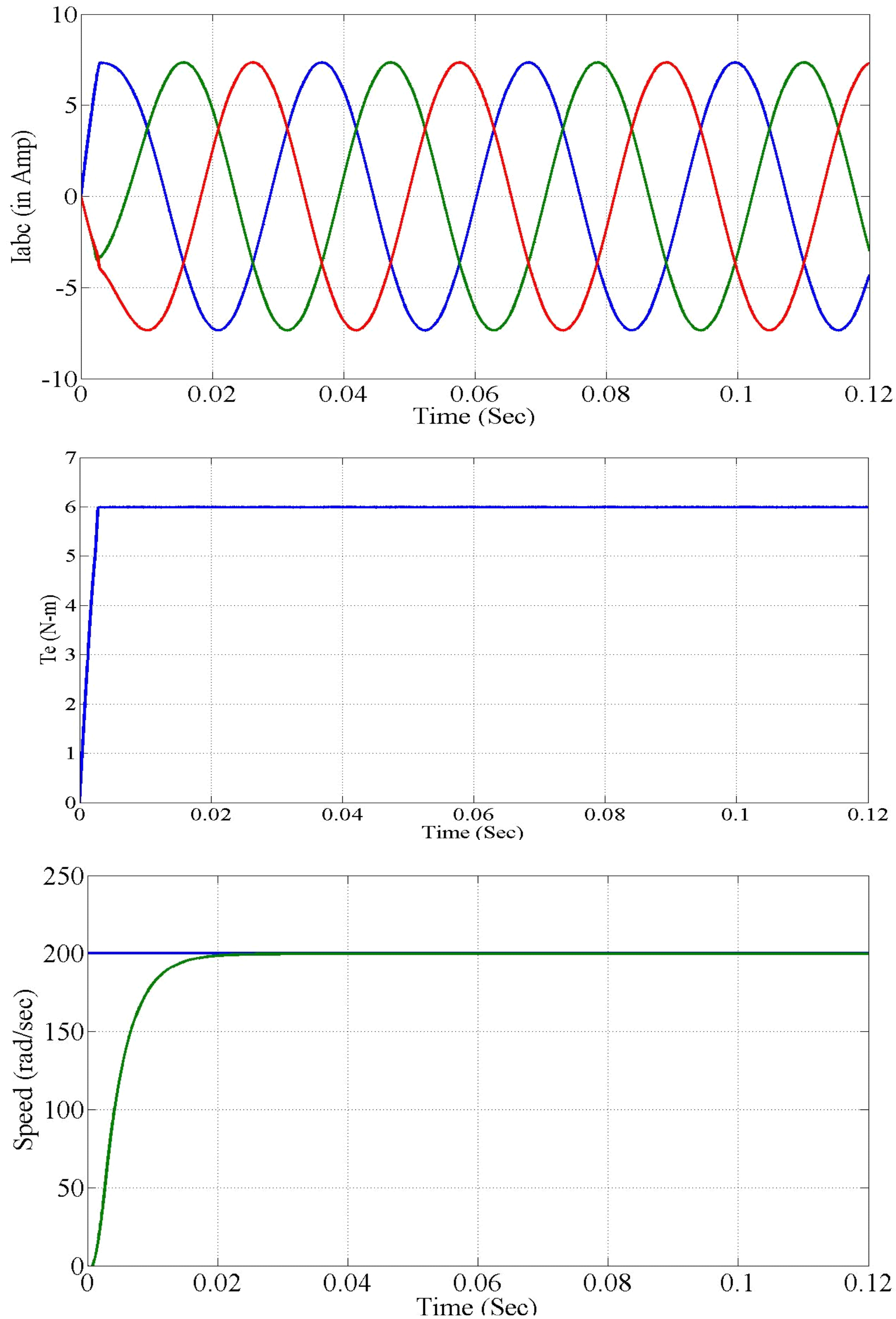
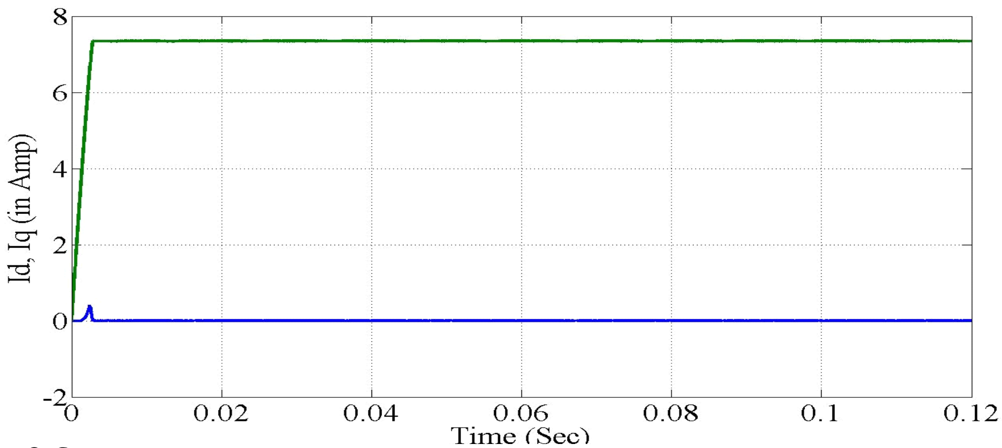


Fig.4.1.2 (a) Stator current waveform; (b) Response of T_e; (c) Response of speed during steady state conditions using AHBCC

The corresponding d-q component of current is shown in fig.4.1.2 (d) where it is ripple free response due to adaptive band hysteresis current controller and similarly fig.4.1.1 (e) shows ripple free variation of stator flux in x-y plot.



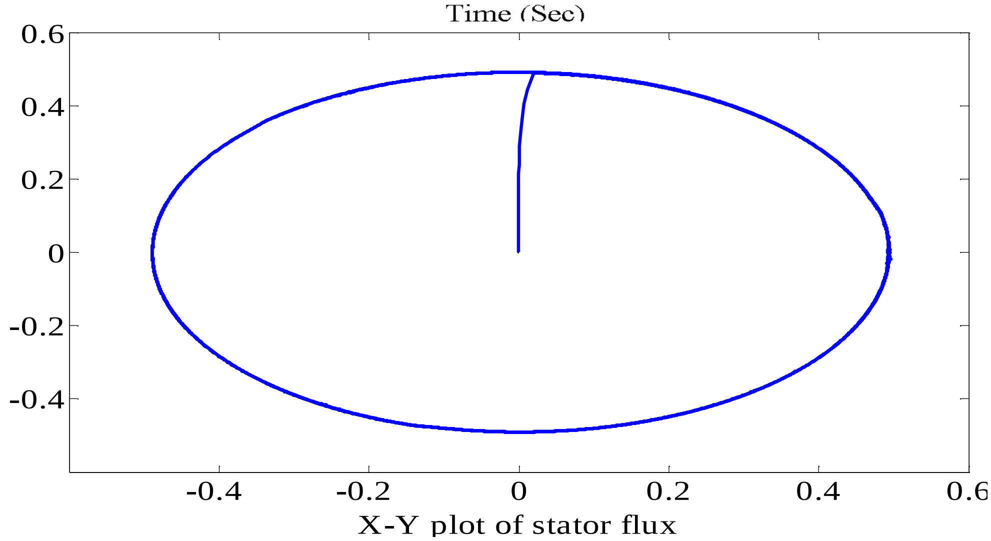


Fig.4.1.2 (d) d-q component of current; (e) Response of stator flux during steady state conditions using AHBCC

4.1.3. Result during Transient Condition for Conventional Hysteresis Current Controller:

In this case, all parameter remains kept same but only a variable step load is applied which is varying from 1N-m to 0N-m at the interval of 0.02 sec in place of constant load.

Fig.4.1.3 (a) shows the variation of stator current. From waveform it is clear that whenever there is a change in load the stator current also changing where some notches are observed during load changing and ripple content throughout. Fig. 4.1.3 (b) shows the waveform of electromagnetic torque during transient condition. In this case the steady state is reached within very short duration during the load changing but the ripple content is greater. The motor speed response during transient condition with variable load is shown in fig. 4.1.3 (c) where some hops are observed during the transient period of load changing.

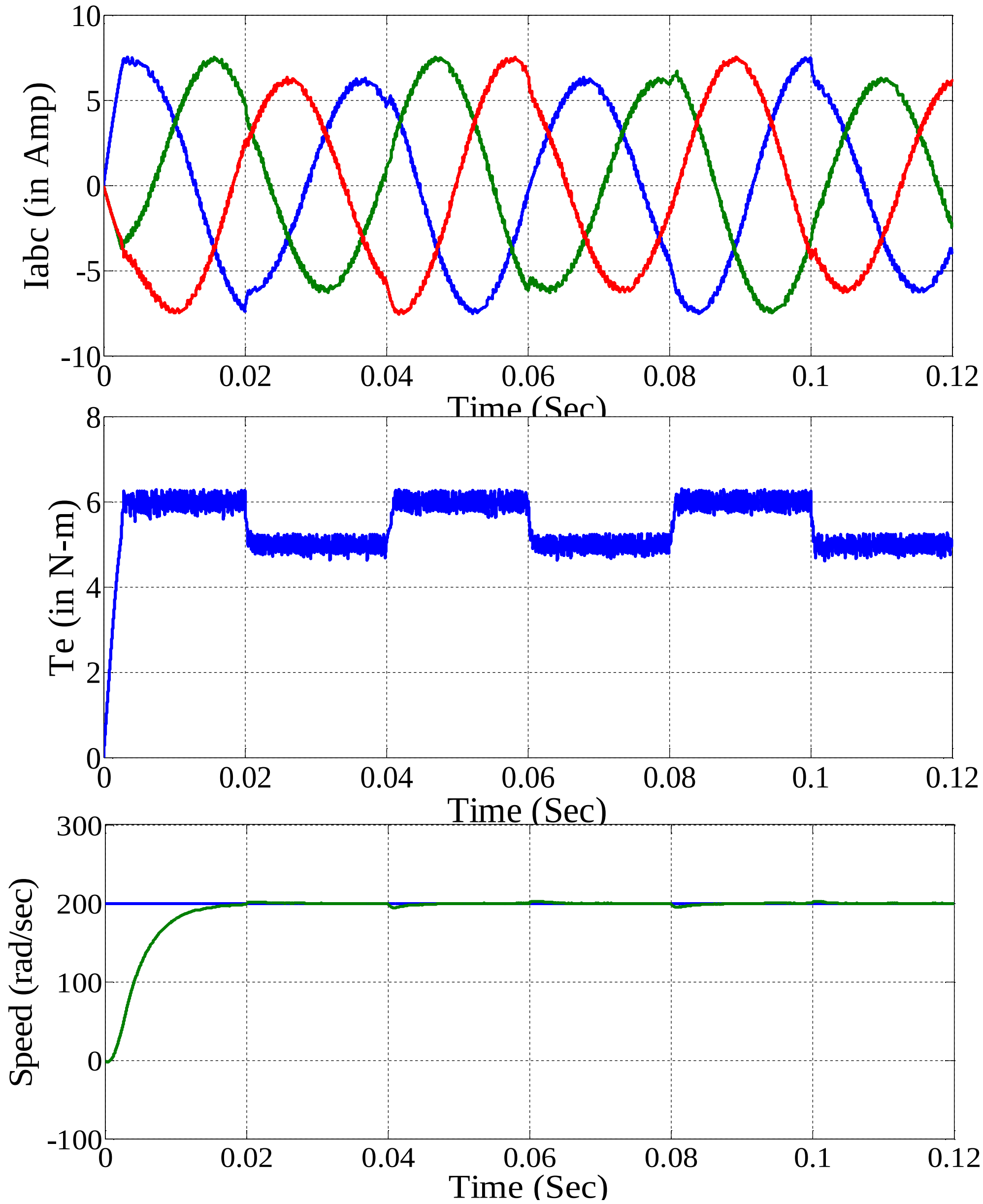


Fig.4.1.3 (a) Stator current waveform;(b) Response of T_e;(c) Response of speed; during transient condition using HBCC.

Fig.4.1.3 (d) shows the variation of d-q component of stator current from which we can observed that only i_q component of current is responsible for T_e and i_d=0 because of constant torque mode of operation. fig.4.1.3 (e) shows the variation of stator flux in x-y plot containing ripples due to fixed band.

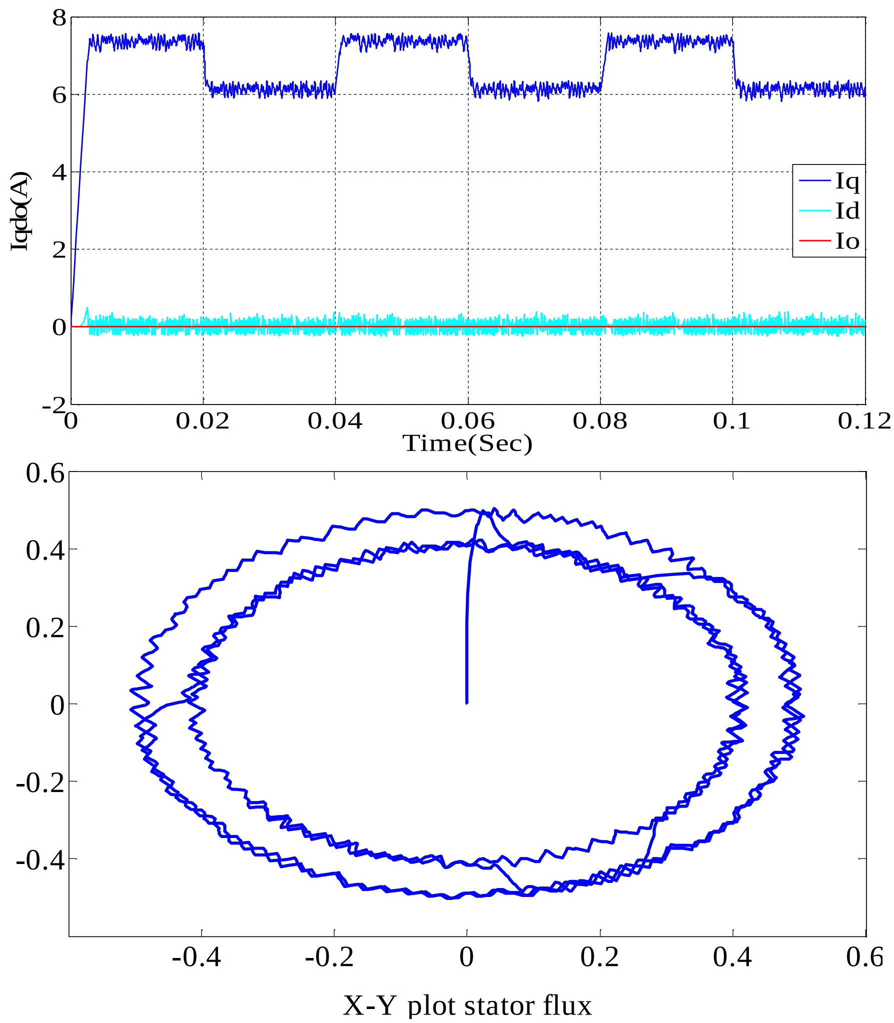
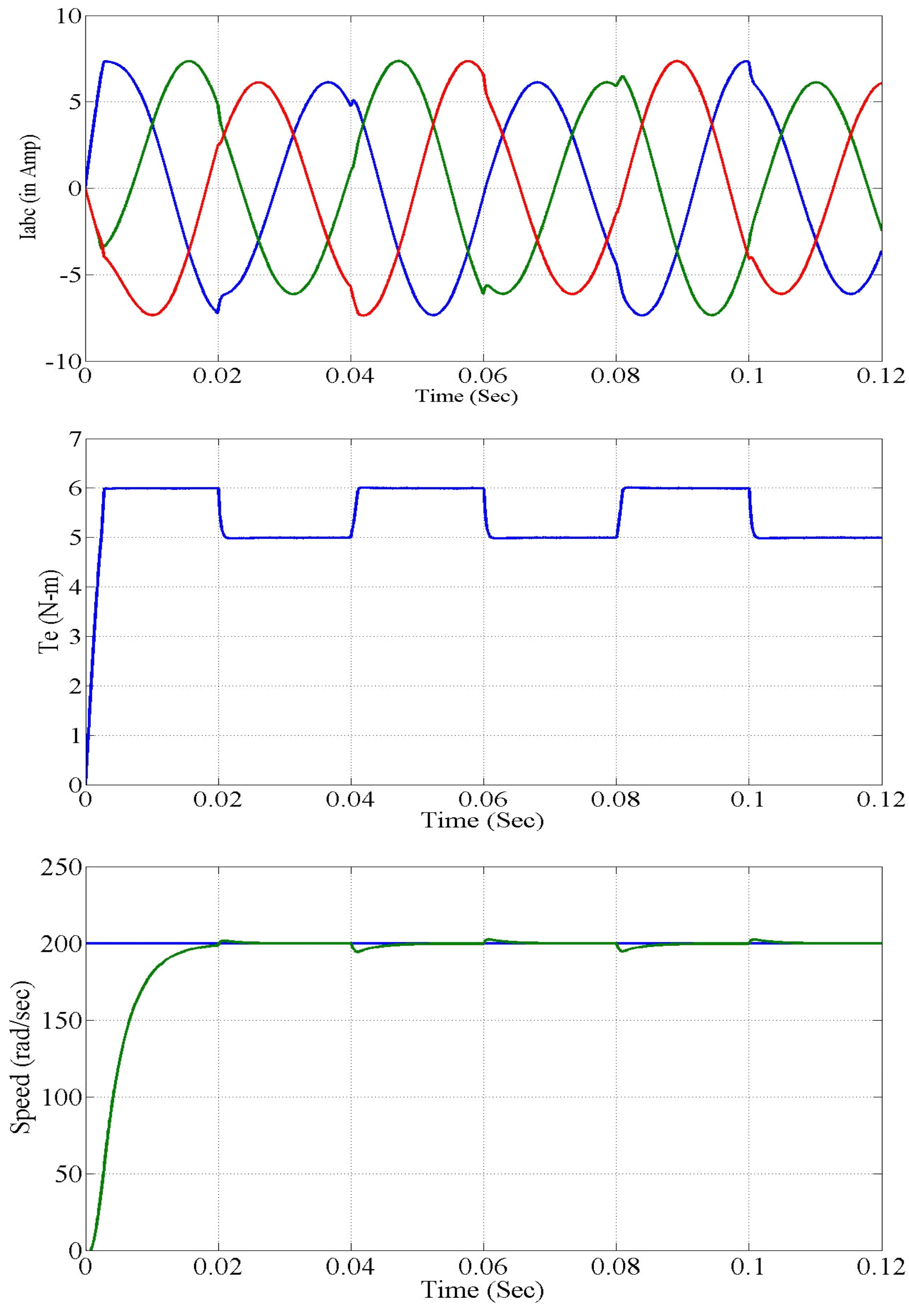


Fig.4.1.3 (d) d-q component of current; (e) Response of stator flux during transient conditions using HBCC

4.1.4. Result during Transient Condition for Adaptive Hysteresis Band Current Controller:

In this case the response of stator current, T_e and motor speed shown in fig. 4.1.4 (a), (b) and (c) respectively where the ripple content reduced highly providing smooth output during transient condition also. Fig. 4.1.4 (d) and (e) shows d-q component of current and the x-y plot of stator flux respectively during transient conditions. The torque ripple and ripple content of stator flux have been reduced drastically due to constant switching frequency operation of adaptive hysteresis current controller.



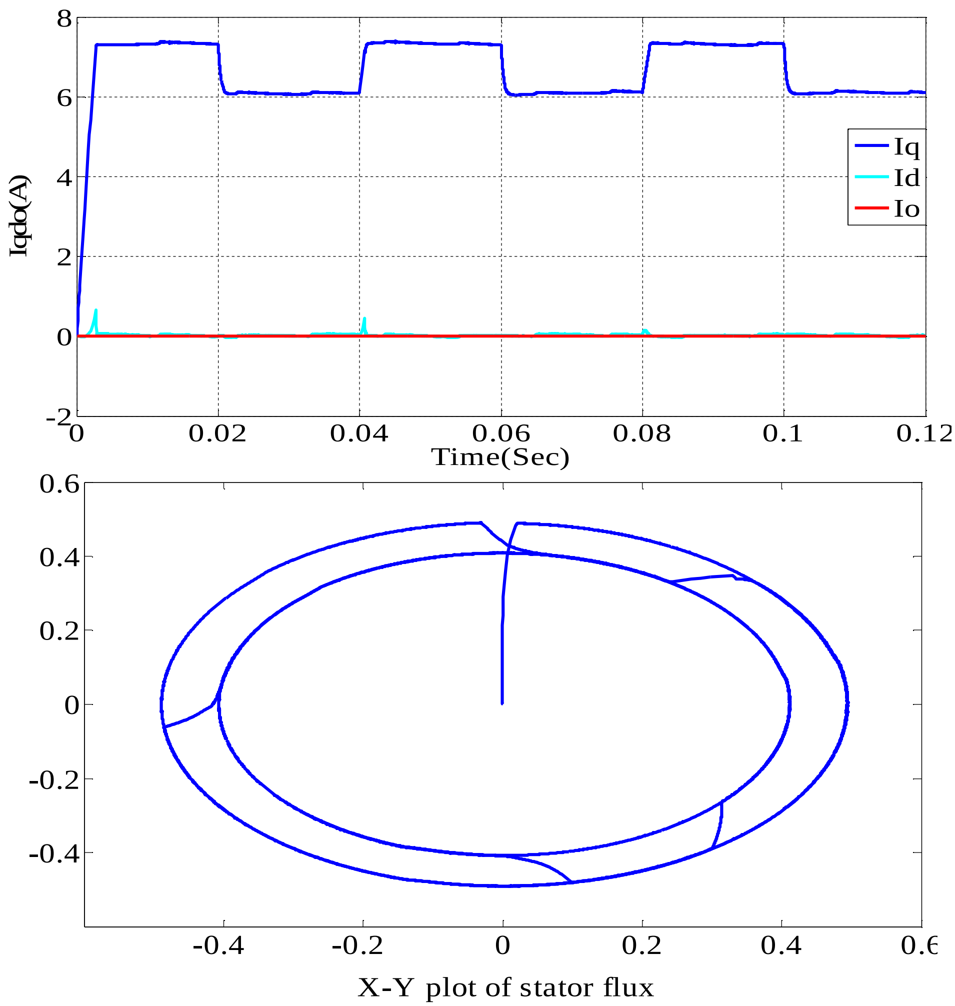


Fig.4.1.4 (a) Stator current waveform;(b) Response of T_e; (c) Response of speed (d) d-q component of current; (e) Response of stator flux during transient conditions using AHBCC.

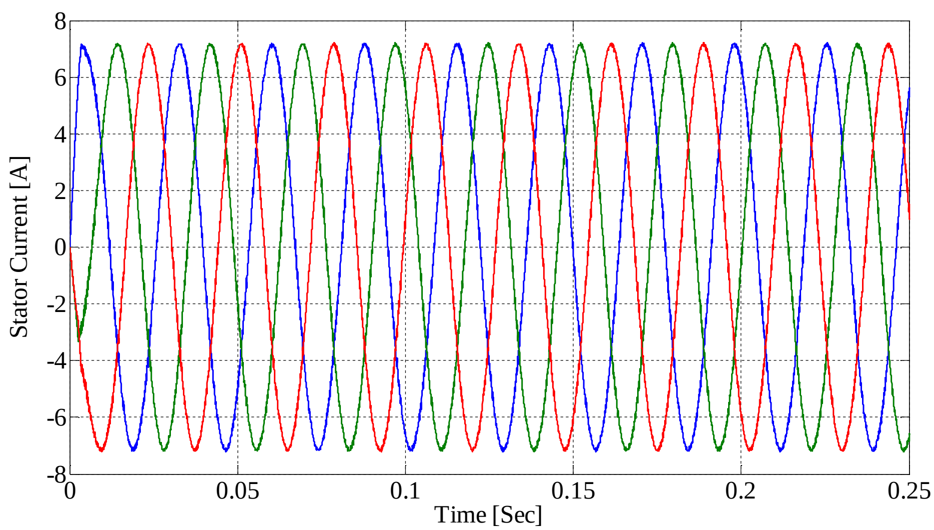
From above simulation waveforms and analysis, it can be reveal that the Adaptive hysteresis band current controller is providing ripple less and smooth responses as compared to Conventional fixed band hysteresis current controller. So for our proposed IPMSM drive system Adaptive hysteresis band current controller has been chosen and integrated as current controller for further analysis and comparison of drive performances using PI, Fuzzy and Hybrid PI-FLC as different speed controller so as to achieve a better speed controller as well for further enhancement of performance of proposed IPMSM drive system. The performance comparison of different speed controller is analyzed in next section.

4.2. Performance Comparison Using Different Speed Controllers:

In this section, performance of drive system using PI, Fuzzy and Hybrid PI-FLC as different speed controller has been demonstrated at no-load, variable load & variable speed conditions. For all condition operation Adaptive hysteresis band current controller has been integrated as inner current controller. The MATLAB/Simulation is focused on minimization of the ripple contents of stator current, torque and improving the motor speed response under transient and steady state operating conditions.

4.2.1. Result during No-load Condition for Conventional PI Controller:

For this case the gain constants are set as K_p= 0.3581 & K_i= 129.9014 and the reference speed to be track is 230 rad/sec. Fig.4.2.1 (a) shows the 3-phase stator current which does not contains any disturbances while fig.4.2.1 (b) shows smooth response of electromagnetic torque and fig.4.2.1 (c) rotor speed where the ripple contents of the rotor speed are 2.2 rpm and settling time is 0.0495 sec.



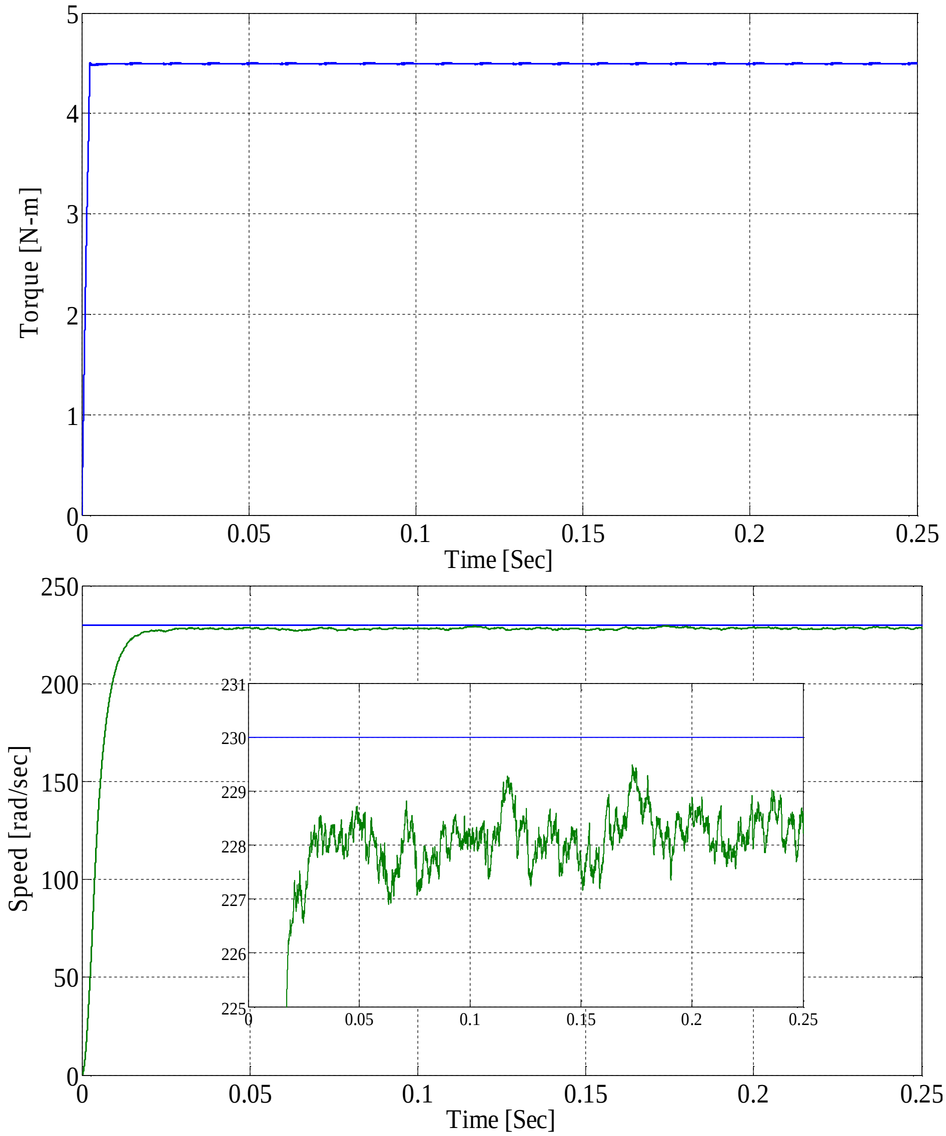


Fig.4.2.1 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using PI controller during No-load.

4.2.2. Result during No-load Condition for Fuzzy Logic Controller:

For this case a 5×5 triangular MF for both inputs as well as output variables of FLC, Fuzzy implication using Mamdani's **min** operators and Defuzzification using Centroid method has been implemented for designed FLC. Fig.4.2.2 (a) shows the 3-phase stator current, fig.4.2.2 (b) shows response of electromagnetic torque and fig.4.2.2 (c) rotor speed where the ripple contents of the rotor speed are 1.55 rpm and settling time is 0.045 sec.

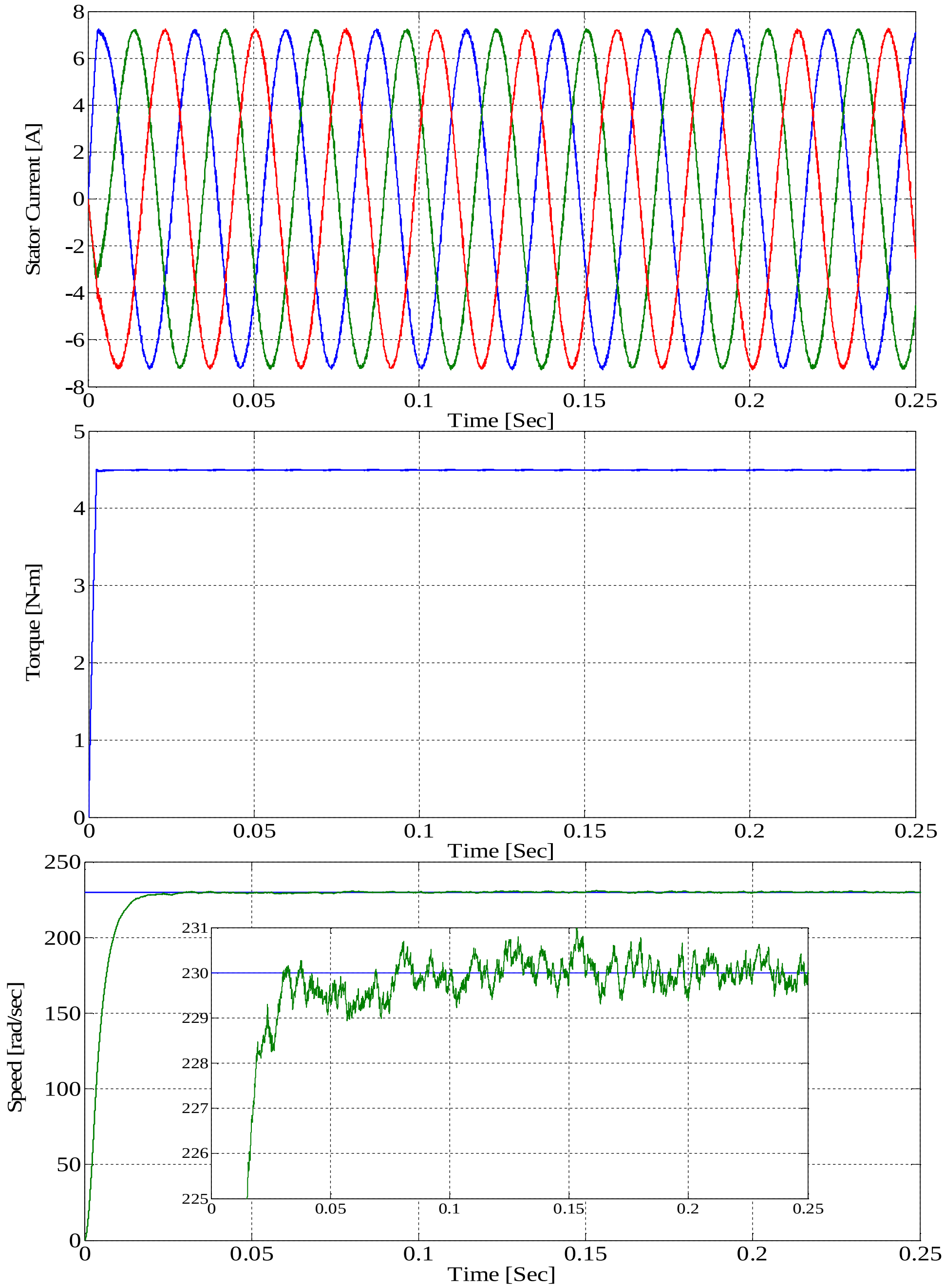


Fig.4.2.2 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using FLC during No-load.

4.2.3. Result during No-load Condition for Hybrid PI-FLC:

Fig.4.2.3 (a) shows the 3-phase stator current, fig.4.2.3 (b) shows response of electromagnetic torque and fig.4.2.3 (c) rotor speed where the ripple contents of the rotor speed are 1.20 rpm and settling time is 0.042 sec. So the responses obtained in this case are little improved as compared to Conventional PI and FLC.

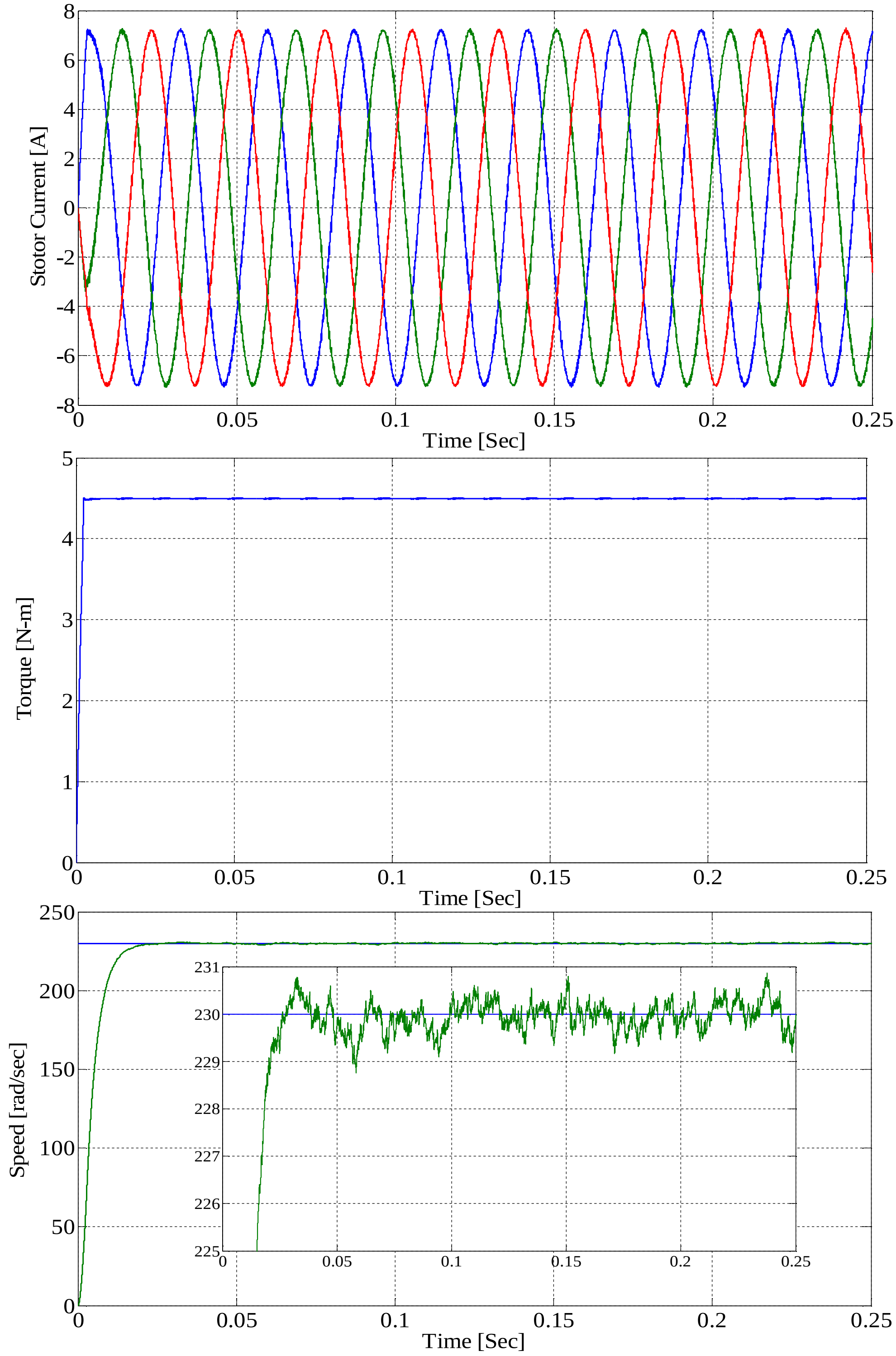
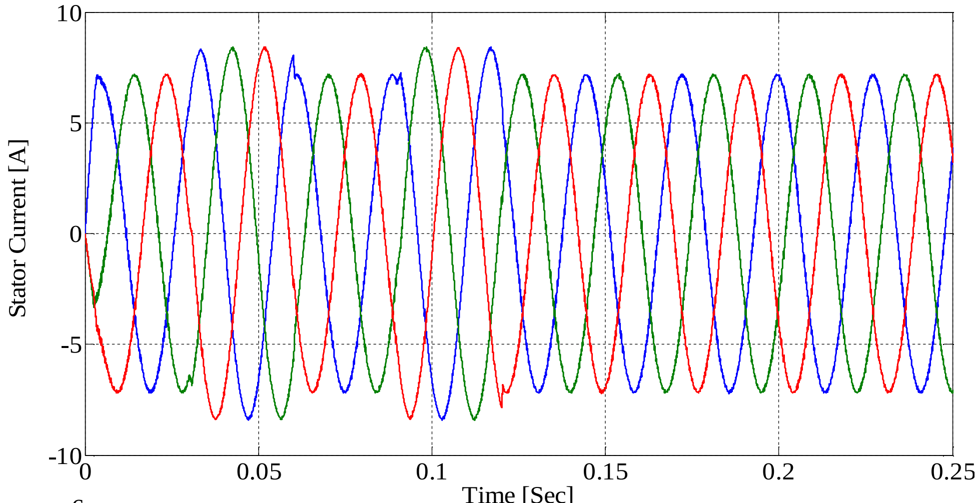
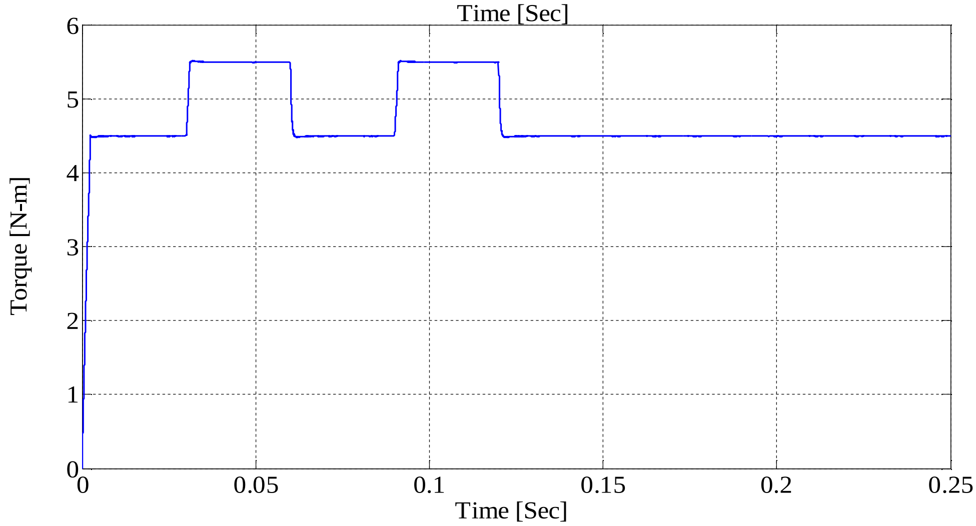


Fig.4.2.3 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using Hybrid PI-FLC during No-load.

4.2.4. Result during Variable Load Condition for Conventional PI Controller:

Here a variable load torque from 1 N-m to 0 N-m at a time interval of 0.03 sec is applied with constant reference speed of 230 rad/sec. Fig.4.2.4 (a) shows the 3-phase stator current, fig.4.2.4 (b) shows response of electromagnetic torque and fig.4.2.4 (c) rotor speed responses. Using conventional PI controller we are getting some overshoot (or undershoots) and notches in 3-phase stator current and rotor speed during transient and ripple contents in torque is 0.12 N.m





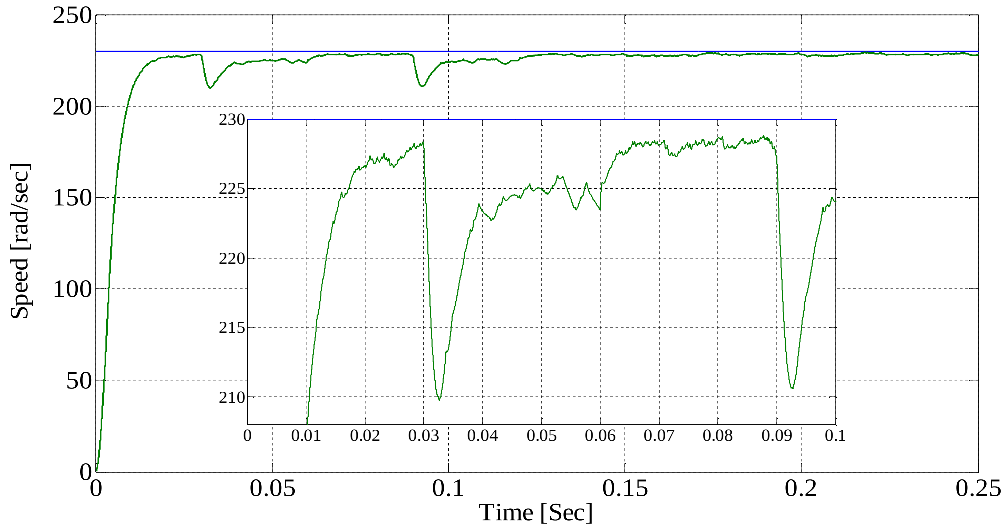
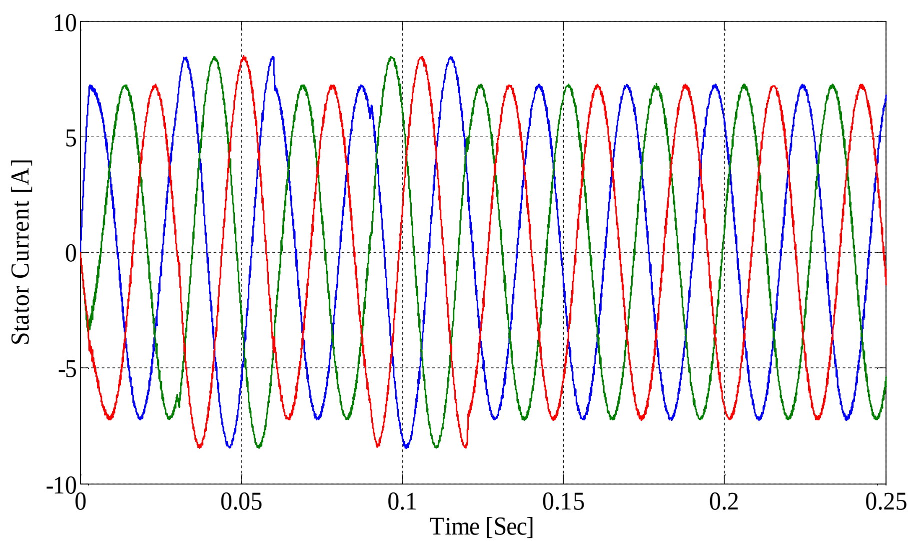


Fig.4.2.4 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using PI during Variable load.

4.2.5. Result during Variable Load Condition for Fuzzy Logic Controller:

Fig.4.2.5 (a) shows the 3-phase stator current, fig.4.2.5 (b) shows response of electromagnetic torque and fig.4.2.5 (c) rotor speed responses. Here it can be observed that the notches in speed response are lesser and ripple contents in torque is 0.09 N-m.



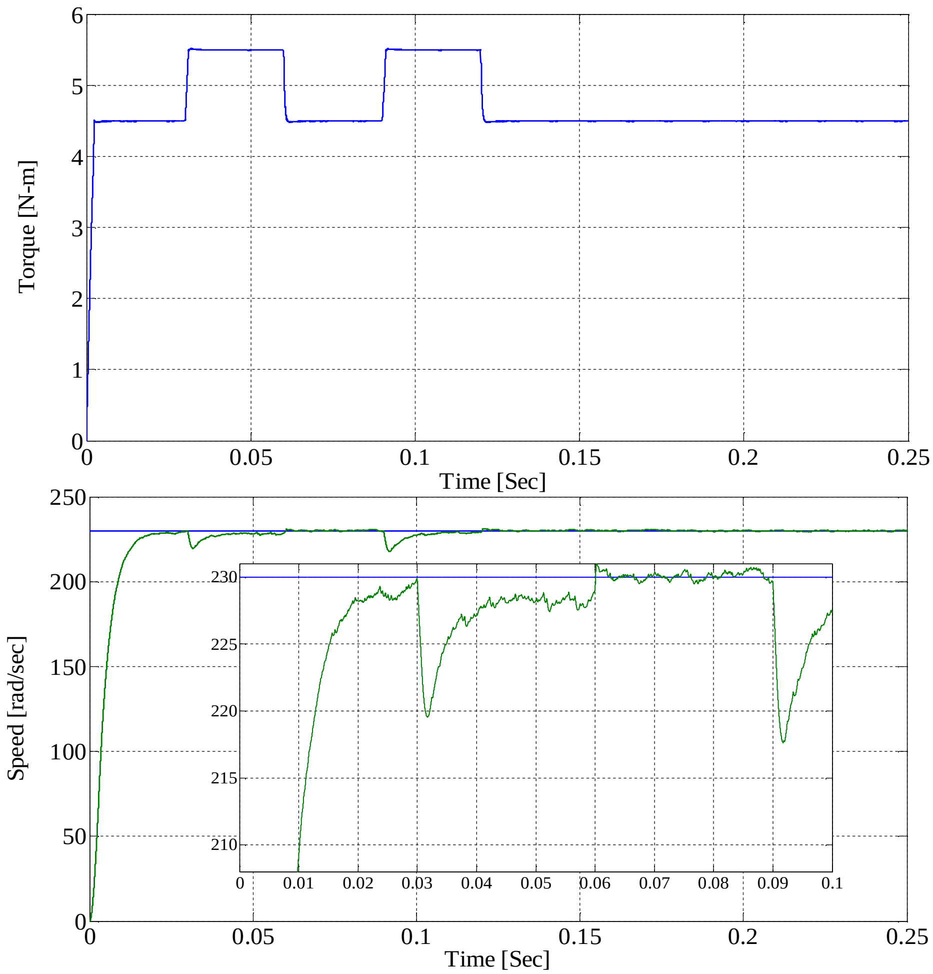


Fig.4.2.5 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using FLC during Variable load.

4.2.6. Result during Variable Load Condition for Hybrid PI-FLC:

Fig.4.2.6 (a) shows the 3-phase stator current, fig.4.2.6 (b) shows response of electromagnetic torque and fig.4.2.6 (c) rotor speed responses. Here also it can be observed that the notches in speed response get smaller than response using conventional PI controller and ripple contents in torque is 0.05 N-m.

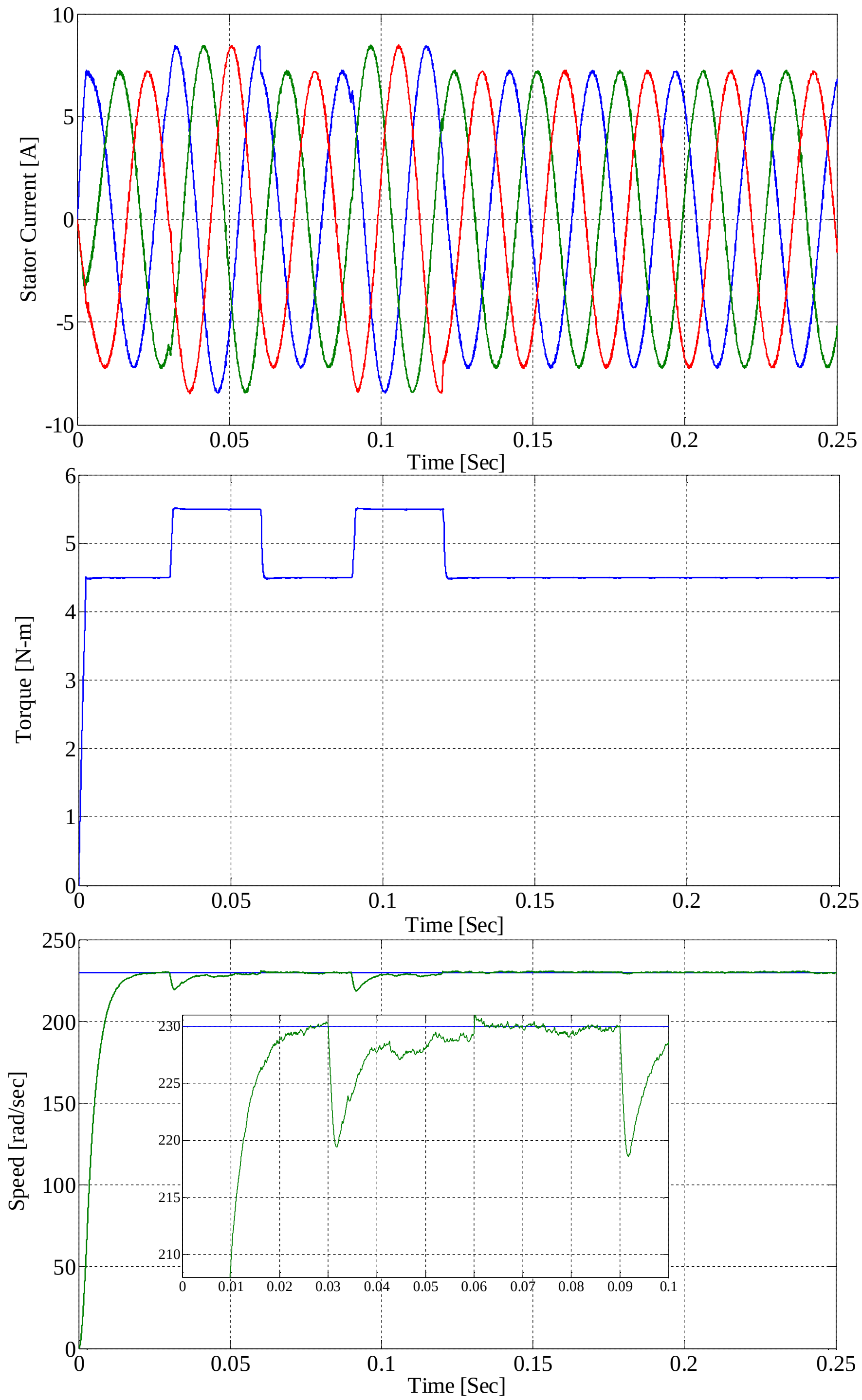


Fig.4.2.6 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using Hybrid PI-FLC during Variable load.

The stator flux in d-q axis for PI, FLC and Hybrid PI-FLC are shown in fig. 4.2.6 (d), (e) & (f) where it is clearly visible the ripple contents in stator flux gradually improved and hence the improved performance using Hybrid PI-FLC can be clearly revealed.

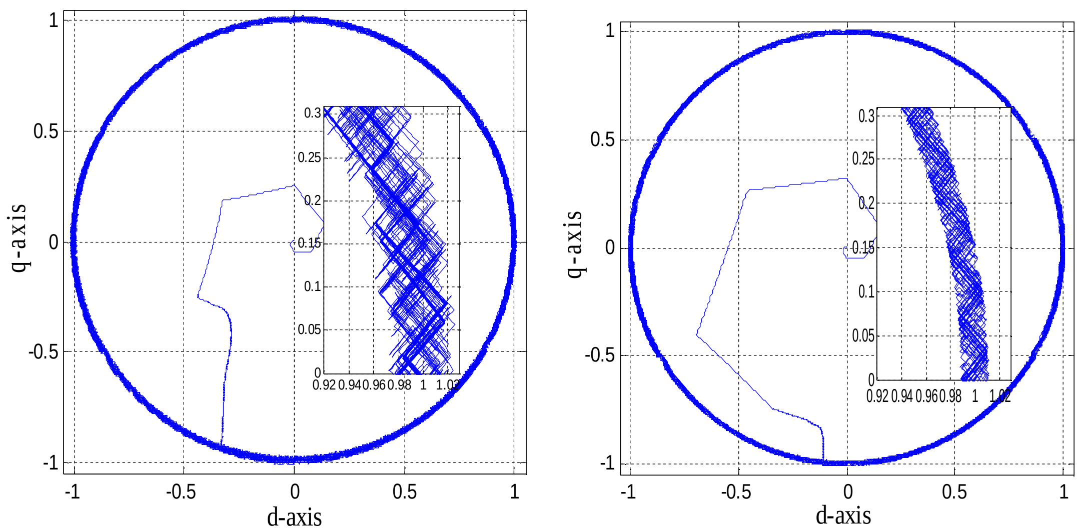


Fig.4.2.6 (d) Stator flux in d-q axis using PI Controller; (e) Stator flux in d-q axis using FLC

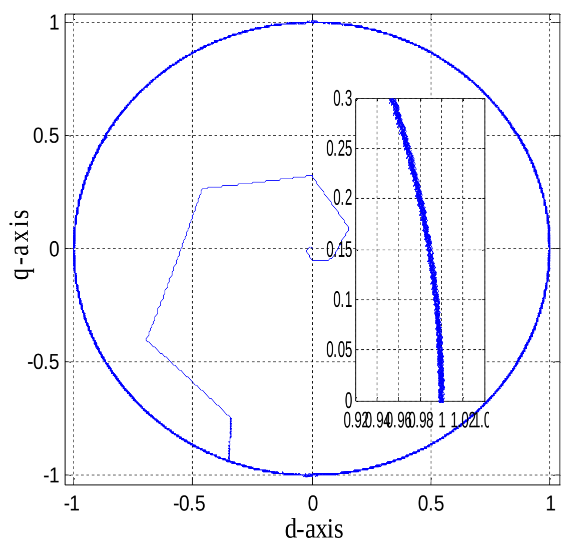


Fig.4.2.6 (f) Stator flux in d-q axis using Hybrid PI-FLC.

4.2.7. Result during Variable Speed Condition for Conventional PI Controller:

Fig.4.2.7 (a) shows the 3-phase stator current containing some ripple, fig.4.2.7 (b) shows response of electromagnetic torque which also contain some ripple and fig.4.2.7 (c) rotor speed responses. The ripple content in torque under load condition is 0.25 N.m.

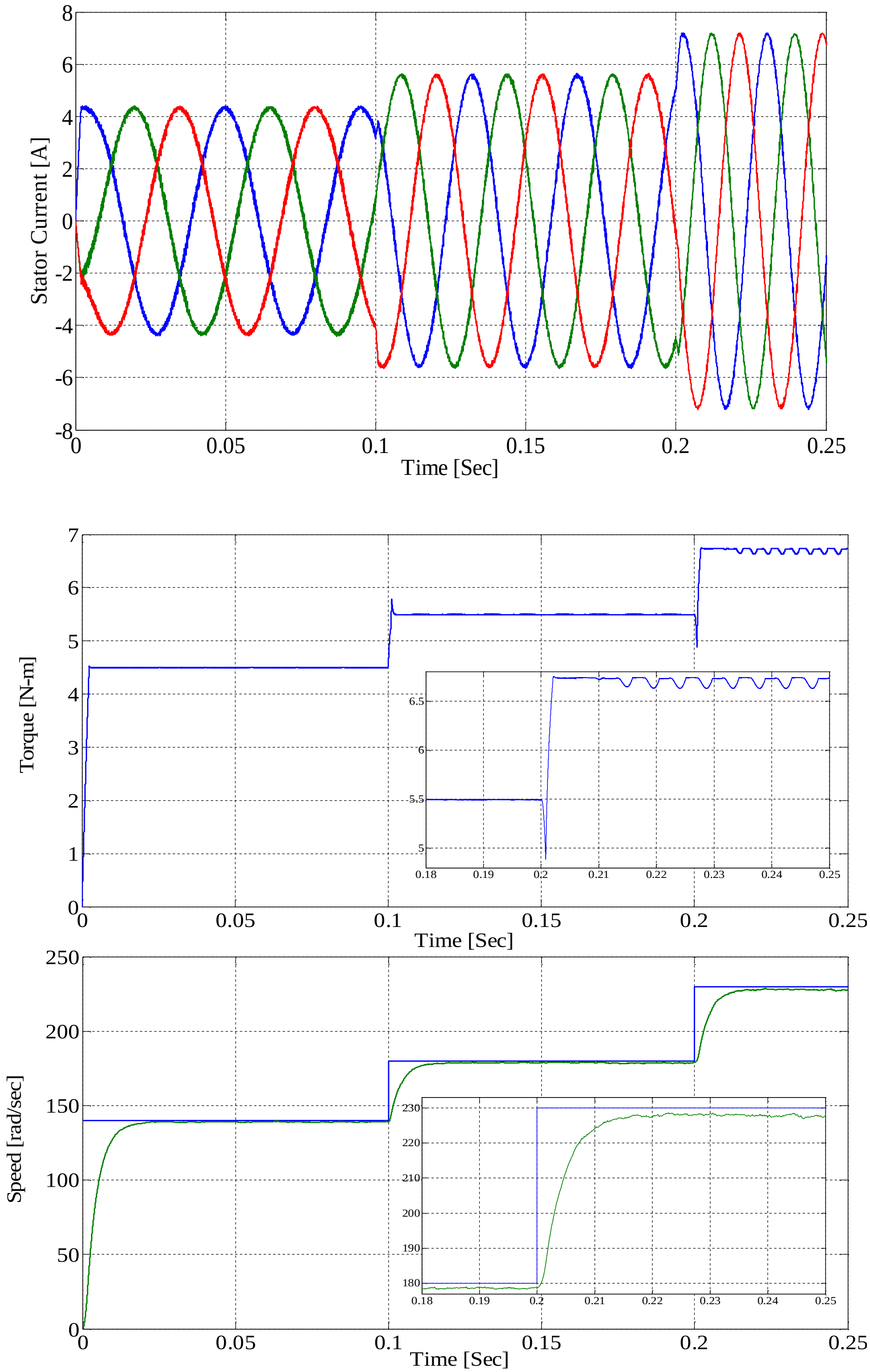
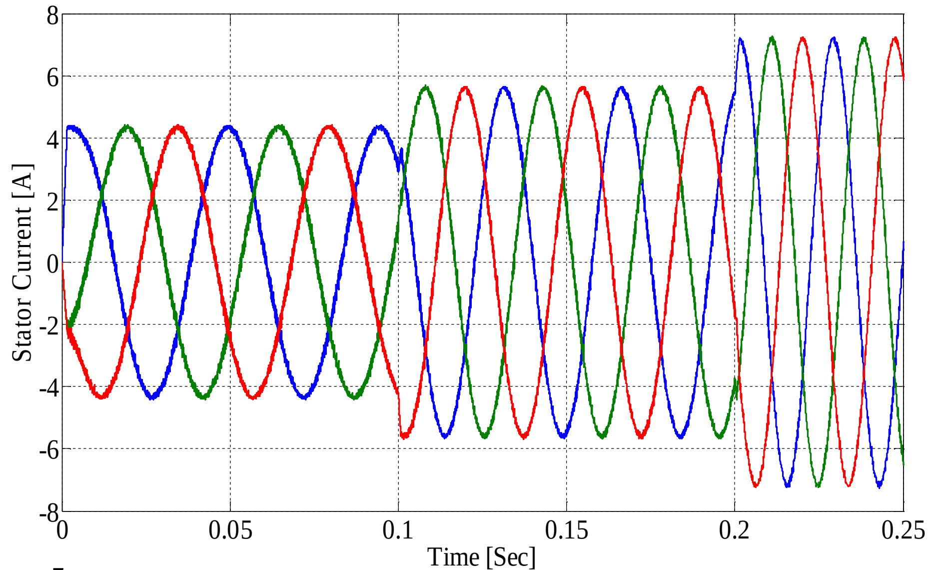
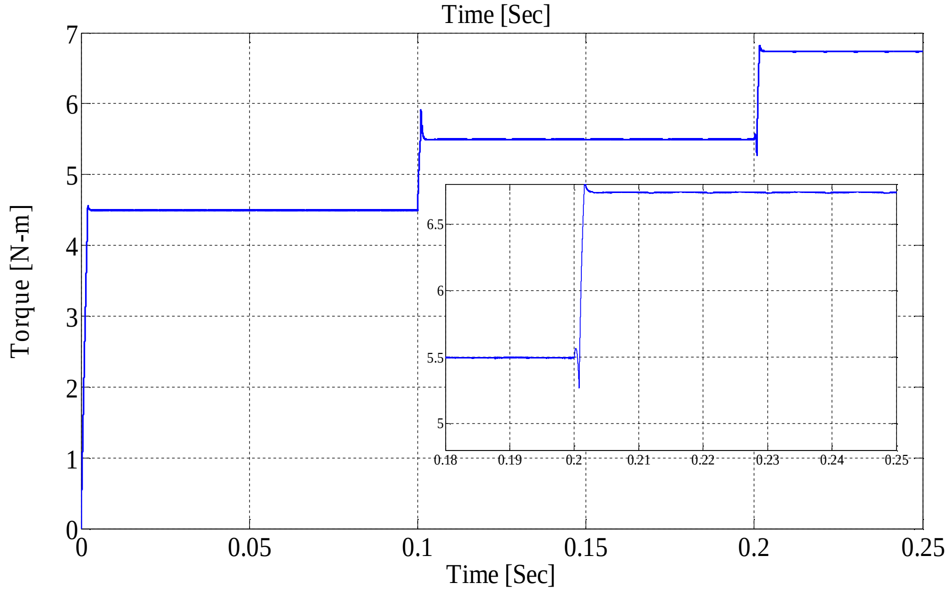


Fig.4.2.7 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using PI Controller during Variable speed condition.

4.2.8. Result during Variable Speed Condition for Fuzzy Logic Controller:

Fig.4.2.8 (a) shows the 3-phase stator current, fig.4.2.8 (b) shows response of electromagnetic torque and fig.4.2.8 (c) rotor speed responses where the ripple content and notches magnitudes in stator current and Torque responses are little lesser. The ripple content in torque under load condition is 0.12 N.m.





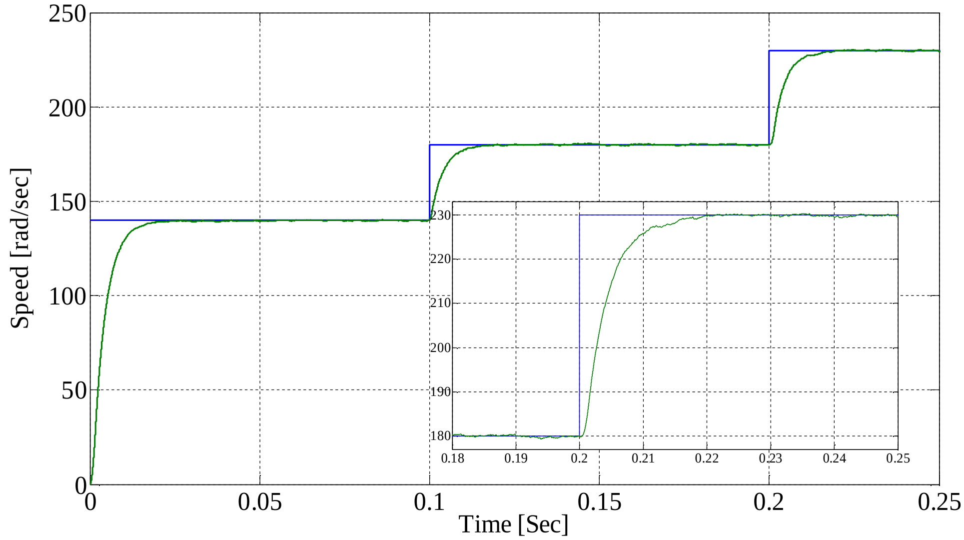
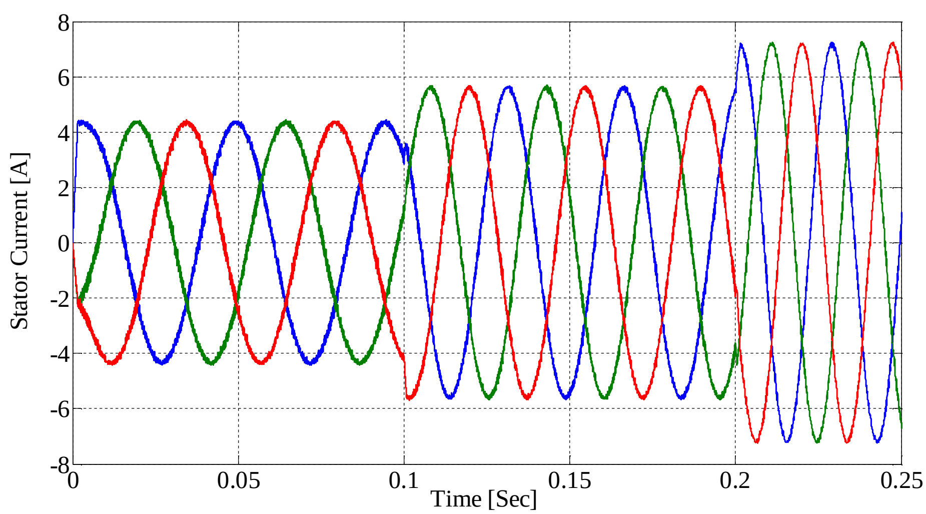


Fig.4.2.8 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using FLC during Variable speed condition.

4.2.9. Result during Variable Speed Condition for Hybrid PI-FLC:

Fig.4.2.9 (a) shows the 3-phase stator current; fig.4.2.9 (b) shows response of electromagnetic torque and fig.4.2.9 (c) rotor speed responses with lesser ripple and notches in the stator current and torque response than the PI & FLC. The ripple content in torque under load condition is 0.05 N.m. So it can be revealed that the performance of IPMSM drive system is get improved using Hybrid PI-FLC.



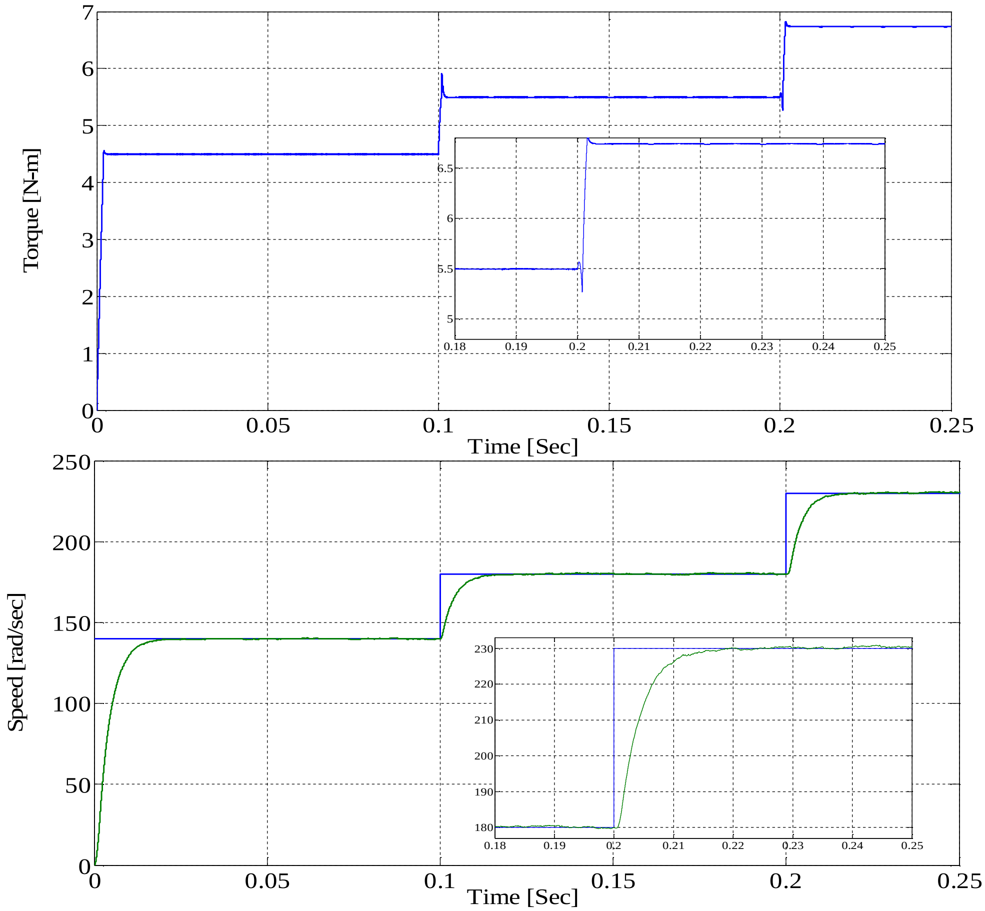


Fig.4.2.9 (a) 3-phase stator current; (b) electromagnetic torque response; and (c) Rotor speed responses using Hybrid PI-FLC during Variable speed condition.

4.3. Summary:

In this chapter a comprehending results and responses of proposed IPMSM drive system using two integrated control strategy has been presented which is modelled and verified in the MATLAB/Simulink environment. From the given responses of speed control of IPMSM drive system using different current controller and speed controller techniques, we can come to the conclusion that the Adaptive hysteresis band current controller has reduces the torque ripple, minimizes the current error and maintain the switching frequency approximately constant as compared to conventional hysteresis controller. While among different speed controller, Hybrid PI-FLC is giving better response thane others during both steady state and transient conditions.

CHAPTER 5

Conclusion and Future Work

5.1. Conclusion:

This dissertation is mainly emphasized on the study of performance of IPMSM drive system using different current controllers in inner loop and speed controllers in outer loop. In order to run IPM motor at the desired speed, a closed loop with vector control IPMSM drive was successfully designed and operated in constant torque mode. The feasibility of the above mentioned integrated control strategy is modelled and verified in the MATLAB/Simulink environment for effectiveness of the study.

From the obtained results we observed that, during both steady-state and transient conditions Adaptive hysteresis current controller reduces the torque ripple, minimize the current error and maintain the switching frequency approximately constant as compared to conventional hysteresis controller as inner current controllers. While comparing with the PI-controller, the FLC and hybrid PI-FLC techniques has superior performance. The ripple contents of stator current, flux and torque are minimised considerably and the dynamic speed response is also improved with the proposed control technique under transient and steady state operating conditions. The simulation results are presented in forward motoring under no-load, load and sudden change in speed operating conditions

So the proposed model with Hybrid PI-FLC as speed controller and Adaptive hysteresis band current controller as current controller is providing smooth and improved performances as compared to other controllers that have been taken in consideration in this dissertation.

5.2. Future Work:

Here it is focused on the performance enhancement of IPMSM drives and simulation work has been done for its analysis. However, due to equipment limitations these methods could not tested practically. So in the future work the results obtained for proposed control technique from simulation environment will be validate with experimental results. In addition to that, analysis of performance of PMSM drive implementing further advanced and intelligent controller like Adaptive fuzzy controller and implementation of such controller in both speed and current loop can be carry out. The analysis also can be extended to above rated speed operation i.e. Flux weakening region.

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APPENDIX A

Nominal Parameters taken for IPMSM Drive system are: 3-Phase PMSM, 220 V, 2.5 kW, 3 A, 50 Hz, N=3000 rpm, P = 4, R_s = 4.3 Ω, λ_f = 0.272Wb, L_d = 27mH, L_q = 67mH, V_{dc} = 300V, J= 0.000179 kg m^2, B = 0.05 N-m/rad/sec, f_s = 500 KHz.

PUBLICATION

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